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Waterways Experiment
Station

Final Report
CPAR-SL-97-1
August 1997

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Computer Software Program for On-Line Process Control of Production of Portland-Cement Concrete

by

Steven A. Ragan, Billy D. Neeley

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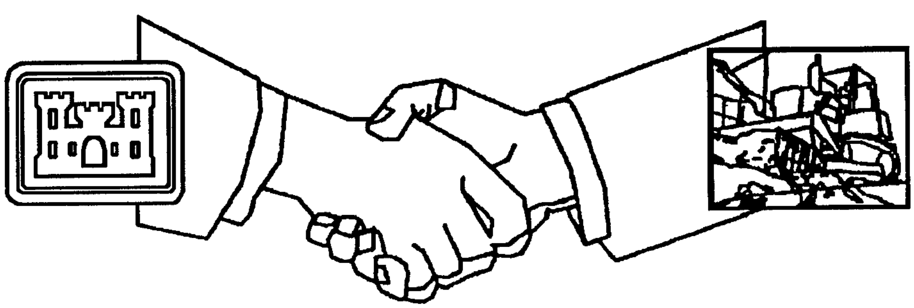

A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

Construction Productivity Advancement Research (CPAR) Program

Technical Report CPAR-SL-97-1
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by Steven A. Ragan, Billy D. Neeley

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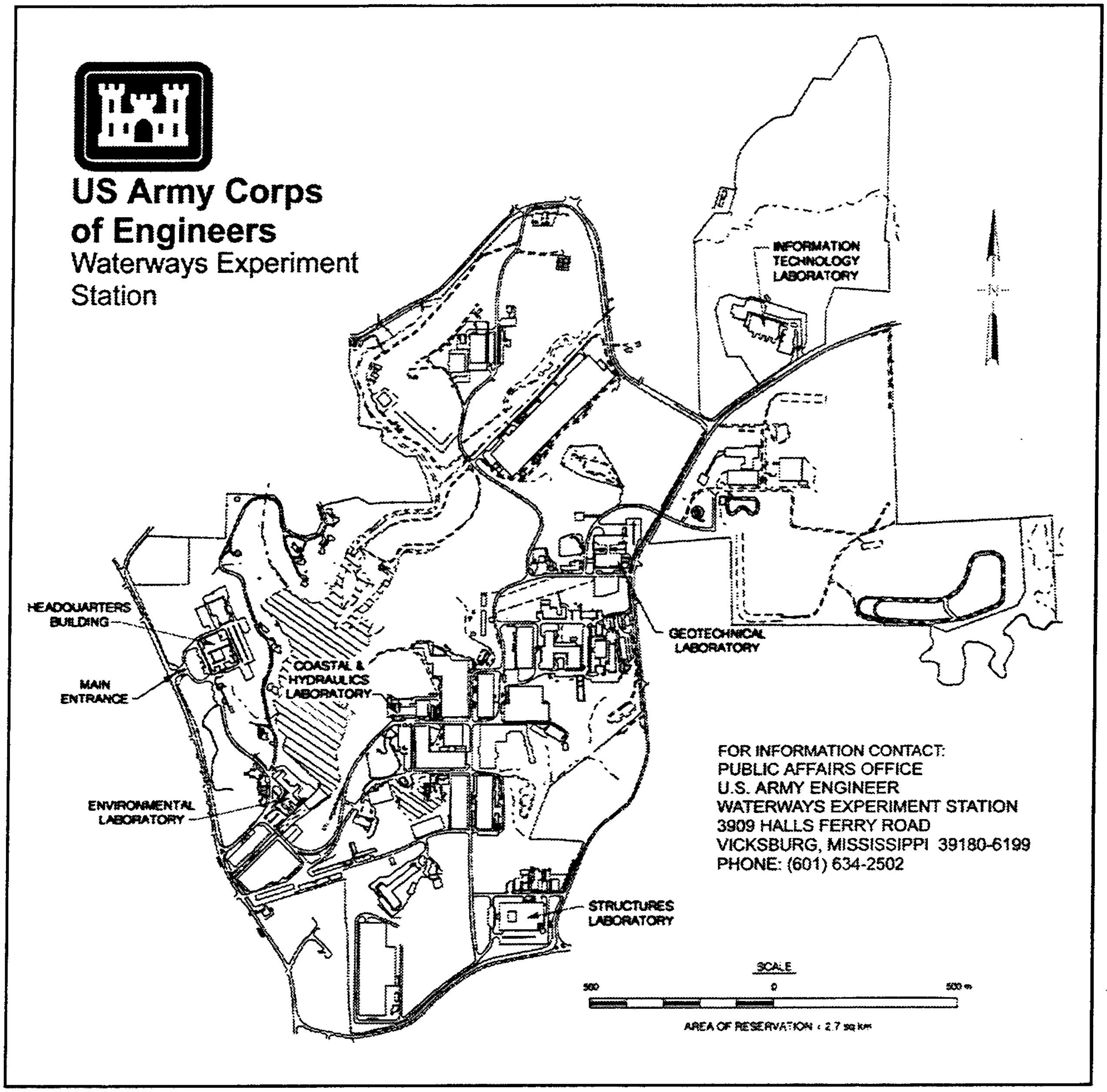

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Contents

Preface

The investigation described in this report was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE), by the Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), in cooperation with Shilstone Software Co., Dallas, TX. This cooperative research and development agreement was a part of the Construction Productivity Advancement Research (CPAR) Program. The HQUSACE Technical Monitors were Messrs. M. K. Lee and Daniel Chen.

Separate efforts were performed by WES and Shilstone Software Co. to meet the study objectives. Experiments conducted at WES were under the general supervision of Messrs. Bryant Mather, Director, SL; John Ehrgott, Assistant Director, SL; William F. McCleese, CPAR point of contact at WES; and Dr. Paul Mlakar, Chief, Concrete and Materials Division (CMD), SL. Direct supervision was provided by Mr. Steven A. Ragan, former Chief, Engineering Mechanics Branch (EMB), CMD, and Mr. Ed O'Neil, Acting Chief, EMB, CMD. Assistance in the WES investigation was provided by Messrs. Billy D. Neeley, Michael K. Lloyd, Percy Collins, Roy C. Gill, and Ms. Linda Mayfield, EMB, CMD, and by Mr. John Cook, Engineering Sciences Branch, CMD. The computer programming conducted by Shilstone Software Co. was under the general supervision of Mr. James Shilstone, Sr. Direct supervision was provided by Mr. James Shilstone, Jr. This report was prepared by Messrs. Ragan and Neeley.

At the time of preparation of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic yards	0.7645549	cubic metres
inches	25.4	millimetres
miles (U.S. statute)	1.609347	kilometres
ounces (U.S. fluid)	0.02957353	cubic decimetres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.5932764	kilograms per cubic metre

1 Introduction

Project Background

Concrete production today usually involves batching materials based upon approved mixture proportions which are developed in a laboratory or from past production experience. Although this practice works well when the materials and production and placement conditions match those at the time the mixture was proportioned, problems may occur if variations occur. These variations may include changes in concrete material properties, changes in fresh concrete workability requirements, and changes in construction needs. Typically, the only adjustments made to constant batch weights derived from the approved proportions are those necessary to account for changes in aggregate moisture content. This is done to maintain the water-cement ratio (w/c) and slump as constant as possible. In some cases, even this adjustment to the aggregate and water batch weights is ignored, and water is simply added or deleted in an effort to produce concrete within the specified slump range. This practice completely ignores w/c and often results in large fluctuations in concrete strength and durability.

In an effort to reduce the variability associated with commercial concrete production in the United States, Shilstone Software Co. has developed an IBM PC compatible computer software program, SmartPlant, to control concrete batching operations in such a manner as to produce uniform concrete having the desired level of quality. SmartPlant has been designed to replace current concrete plant control computer software, which typically stores mixture proportions by saturated surface-dry batch weights. Instead, SmartPlant characterizes a mixture by means of a composite mixture formula or model which is somewhat analogous to the methodology followed in asphaltic concrete mixture proportioning. Once the concrete mixture formula or model is established, the program uses a range of quality control input data to ascertain variations in material properties and construction conditions and to adjust the concrete mixture proportions accordingly. Shilstone Software Co. has stated that SmartPlant will ultimately be supported by four data systems. The first will be for materials with subsystems for aggregates, cement, fly ash, and admixtures. The aggregate data will be generated from standard American Society for Testing and Materials (ASTM) tests, and data for the other materials will be derived from mill tests. The second database is described as a performance database and will be a statistical program

into which results of selected fresh concrete tests and compressive strength tests are entered. This program uses both standard deviation, time-line histories, and multiple regression to analyze data. The third system will consider construction needs in making adjustments in mixture proportions based upon a relationship between placing and finishing needs and the volume needed in the mixture. The fourth system will evaluate variations in mixture temperature and transit time and adjust cementitious material weights to account for anticipated variations in compressive strength.

As of the date of this report, three Shilstone Software Co. computer programs were available for integration into SmartPlant. These included seeMIX, seeSTAT, and seeMAT. SeeMIX is a mixture proportioning program which enables the user to calculate and adjust mixture proportions based either upon procedures outlined in American Concrete Institute (ACI) (ACI 1994b) or upon those developed by Shilstone Software Co. which use a combined coarse and fine aggregate blend for establishing the mixture model. SeeSTAT is a statistical analysis program capable of analyzing and graphically presenting results of selected fresh and hardened concrete tests. SeeMAT is a materials database program capable of tracking a variety of aggregate and cementitious material quality-control and quality-assurance test data. The integration of these component computer programs into a single computer program such as SmartPlant requires an extensive knowledge of both computer programming and concrete technology. To accomplish the task, Shilstone Software Co. and the U.S. Army Engineer Waterways Experiment Station (WES) entered into a Cooperative Research and Development Agreement (CRDA) under the Construction Productivity Advancement Research (CPAR) Program. The CPAR Program is a cost-shared research and development program aimed at assisting the U.S. construction industry in improving productivity by facilitating development and application of advanced technologies. As the productivity and competitiveness of the U.S construction industry is advanced, savings will be realized for the Government, and the U.S. economy will be boosted. This document is the final report of the work undertaken under Fiscal Year 1989 CPAR Work Unit 32608.

Overall Project Objective

The objective of this investigation was to develop a computer software program, SmartPlant, which will reduce the cost of concrete mixtures and increase construction productivity by minimizing the adverse effects of material and mixture variations upon concrete construction operations.

Scope of Investigation

During this investigation, Shilstone Software Co. was responsible for the overall development of SmartPlant, including the development or revision of the component software forming the foundation of SmartPlant. Shilstone Software Co. also focused extensive attention and effort on advancing the mixture proportioning technology used in the seeMIX and SmartPlant computer programs by participating in the preparation of draft documents for use by ACI and ASTM and publishing and presenting numerous technical papers on the subject.

The focus of the WES effort during the investigation was the evaluation of the component programs integrated into SmartPlant and the evaluation of the SmartPlant program. Most attention was given to the seeMIX program, since the technology used by this computer program was the most novel. A laboratory evaluation of the program was conducted in which simulated paving, structural, and mass concrete mixtures were proportioned using both current ACI proportioning practices and seeMIX technology. A series of fresh and hardened concrete tests was conducted on the mixtures to assess the degree of improvement, if any, achieved when using the seeMIX proportioning technology. In addition, two abbreviated field evaluations of seeMIX were conducted during the investigation. SeeMAT-A, the aggregate database program, was evaluated under field conditions at two U.S. Army Corps of Engineers (USACE) civil works projects. SeeMAT-C and seeMAT-P were evaluated in the laboratory by taking advantage of existing cement and pozzolan test report data. No extensive evaluation was conducted on seeSTAT, since a concurrent evaluation of the program was being conducted under authority of the Corps of Engineers Computer Applications in Geotechnical Engineering (CAGE) Project by the CAGE Materials Quality Assurance Task Group.

During the preparation and execution of the CRDA for this project, an anticipated major WES function was to be the evaluation of the actual SmartPlant computer program. Repeated set backs by Shilstone Software Co. prevented the timely development of the program. Consequently, only a very abbreviated evaluation of the program was possible. At the date of this report, SmartPlant is still under development. Although it is possible to make manual entries into the program and allow it to make suggested adjustments in proportions and batch weights based upon data input, the program cannot be currently used to replace existing batch plant computer controls.

2 Laboratory Evaluation of SeeMix

Mixture-Proportioning Background

Evidence exists that the Romans had a well-developed, although somewhat prescientific, art of making concrete approximately 2,000 years ago using a material composed of certain volcanic slags mixed with burned lime (Vitruvius 1960). This art apparently died until the middle of the 18th century when a natural cement made by burning certain argillaceous limestones was discovered, followed by the development of hydraulic lime. During the 19th century, a rudimentary form of portland cement was being used in England, and natural cements were beginning to be used in quantity in the United States (Bogue 1955). In the early 20th century, a domestic cement industry began to develop in the United States, and portland cement soon supplanted almost all other cements.

During the early stages of portland-cement concrete development, it seems that it was not thought of as being a plastic material that later becomes rigid. Concrete was prepared in a nonplastic state and consolidated in layers by using rammers. The water content of the concrete was considered to be correct if the workman was just able to bring water flush with the surface. Most of the early attempts to provide a scientific foundation for proportioning concrete mixtures were based on considerations of the packing characteristics of the particulate material. Work by Fuller and Thompson (1907) was perhaps the most influential of this kind. Based upon experiments, Fuller and Thompson concluded that there are certain ideal material gradings which can be approximated by parabolic curves expressed as follows:

$$P_t = (d/D)^{1/2} \tag{1}$$

where

p_t = fraction of total solids finer than size d

D = maximum particle size

However, Fuller and Thompson recognized that material graded according to this parabolic equation would result in unworkable mixtures, so they added a provision that at least 7 percent of the total material, by weight, must be finer than 75 μm (No. 200) sieve. Modifications were subsequently made to the Fuller-Thompson grading model by others, including Plum (1950).

In 1918, Abrams published a systematic method of proportioning concrete mixtures which presupposed that a concrete mixture should be workable under a given set of conditions and that it should be able to develop a specified compressive strength (Abrams 1918). He stated that "for given materials, the strength depends only on one factor - the ratio of water to cement," and presented an empirical relationship which estimated compressive strength of concrete as follows:

$$f_c = A/B^{x} = A/B^{1.5(w/c)} \tag{2}$$

where

f_c	=	compressive strength
A	=	empirical constant, usually about 96.5 MPa (14,000 psi)[1]
B	=	constant that depends on the characteristics of the materials, especially the cement, and on the age of test. For 28-days age Abrams found $B = 7$
w/c	=	water-cement ratio, by mass

With the empirical relationship between strength and w/c established, it was required only to find the combination of cement and aggregate that would provide the desired w/c and adequate workability and would contain no more cement than necessary. Abrams found that the water requirement of a concrete mixture can be expressed as the sum of the water requirement of the cement and that of the aggregate. The water requirement of the aggregate was found proportional to the amount of the aggregate used in the mixture and inversely proportional to a term he defined as aggregate fineness modulus.

Modifications of the Abrams' basic concrete proportioning methodology were made by Thaulow (1955), Swayze and Gruenwald (1947), and Walker and Bartel (1947). Each of these modifications essentially dealt with some facet of optimizing the aggregate or total solid materials fineness modulus. In 1923, Talbot and Richart (1923) published a paper on what became known as the mortar-voids method of proportioning mixtures. Like Abrams, their method was based on achieving a specified compressive strength; however, unlike Abrams they selected a voids-cement ratio corresponding to the desired strength and consistency rather than a w/c. Talbot and Richart based the determination of coarse aggregate content on the reasonable maximum limits of solid volume of coarse aggregate per unit volume of concrete. They experimentally found this

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page vii.

limit to generally be between 65 and 75 percent. In their work, they let b stand for the solid-volume fraction of coarse aggregate in concrete and b_o, the solid-volume fraction of a unit volume of coarse aggregate alone. Therefore, they said that the proportion of coarse aggregate should be at the practical limit for the materials and conditions of the work and that the limit would probably correspond to a b/b_o between 0.65 and 0.75.

The developments described in the preceding paragraphs of this chapter form the basis of the mixture proportioning practice given in ACI 211.1 (ACI 1991a). Most of the concrete produced in the United States today is proportioned with the use of this practice, and the Corps of Engineers specifies in CWGS-03301 (Headquarters, Department of the Army 1994a) that cast-in-place structural concrete mixture proportions shall be based on methodology described in ACI 211.1 (ACI 1991a). The Corps also provides mixture-proportioning guidance in Engineer Manual (EM) 1110-2-2000 (Headquarters, Department of the Army 1994b), which states that mass concrete mixtures are also to be proportioned in accordance with ACI 211.1 (ACI 1991a). ACI 211.1 describes methods for determining first approximations of proportions for normal, heavyweight, and mass concrete mixtures. The practice states that these approximate proportions should be checked by trial batches produced in the laboratory or the field and adjusted, as necessary, to produce the desired characteristics of the concrete. The procedure for proportioning normal concrete mixtures is summarized as follows.

Consistency

The stiffest consistency that can be placed "efficiently" should be used. The types of placing equipment and procedures which can place concrete efficiently are not discussed. Recommended consistencies in terms of slump are given in Table 6.3.1, ACI 211.1 (ACI 1991a) of the practice.

Maximum aggregate size

Recognizing the relationship between the maximum size of an aggregate and the mixture water requirement, the procedure recommends the use of the largest nominal maximum-size aggregate (NMSA) that is economically available and consistent with the dimensions of the structure.

Estimation of water content

After the consistency and aggregate size are selected, the first step toward selecting the proportions of cement, aggregate, air, and water is to estimate the water content. This is done with the aid of Table 6.3.3, ACI 211.1 (ACI 1991a). This table is based on work conducted by Lyse, in which he observed that a given quantity of water in a unit volume of concrete will be approximately the same at a given consistency and maximum aggregate size for all cement contents.

Selection of w/c

The maximum permissible w/c or water-cementitious material ratio w/(c+p) may be based on the requirement for strength or durability, or both. Because the permeability of a concrete mixture increases as the w/c increases and because under some conditions a low coefficient of permeability is required, the control of permeability rather than strength may sometimes determine the maximum permissible w/c. When strength is the governing factor, Table 6.3.4(a), ACI 211.1 (ACI 1991a) of the practice may be used; however, the practice states that it is highly desirable to develop the relationship between strength and w/c or w/(c+p) for the materials actually to be used. In severe conditions of exposure, the practice recommends that the maximum permissible w/c or w/(c+p) be kept below the limiting values of Table 6.4.3(b), ACI 211.1 (ACI 1991a). The practice also presents the user with information necessary to convert a target w/c to a weight ratio of cement plus pozzolanic materials, w/(c+p), by either weight or volume equivalency.

Calculation of cement content

Once the w/c or w/(c+p) is selected, the cement content may be calculated by multiplying the estimated water content by the w/c or w/(c+p).

Quantity of coarse aggregate

The quantity of coarse aggregate per unit volume of concrete is estimated using Table 6.3.6, ACI 211.1 (ACI 1991a) in the practice. This table is an adaptation of the Talbot and Richart method, and the quantity of coarse aggregate is expressed in terms of b/b_o. This volume is converted to dry mass of coarse aggregate by multiplying it by the oven-dry-rodded weight per cubic metre of the coarse aggregate. The practice states that for equal workability, the volume of coarse aggregate in a unit volume of concrete is dependent only on its nominal maximum size and the fineness modulus of the fine aggregate. Differences in the amount of mortar required for workability with different aggregates, due to differences in particle shape and grading, are compensated for automatically by differences in oven-dry-rodded void content.

Quantity of fine aggregate

After the quantity of coarse aggregate has been estimated, all ingredients of the concrete mixture except the fine aggregate will have been estimated. The fine aggregate quantity is determined by difference using either the mass or absolute volume method. If the mass of the concrete per unit volume is known or can be estimated from experience, the required mass of fine aggregate is simply the difference between the mass of the fresh concrete and the total mass of all other ingredients. A more exact procedure for calculating the required amount of fine

aggregate involves the use of the volumes displaced by the ingredients. The total volume displaced by the known ingredients is subtracted from the unit volume of concrete to obtain the required volume of fine aggregate. The mass of fine aggregate is determined by multiplying its solid volume by its unit weight. The unit weight of the any material is the product of the unit volume of water and the bulk specific gravity of that material.

Trial batch adjustments

The practice assumes that the procedure will result in a mixture that will prove to be approximately, but not exactly, in accord with specifications. Therefore, it recommends that only sufficient water be added to the mixture to produce the required slump, regardless of the amount assumed in selecting the trial proportions. This amounts to retracing the steps outlined above on the basis of the newly established water content. Final adjustments in the mixture proportions may be required while the concrete is being placed onsite, taking into account the difference between the characteristics of large and small batches of the same mixture and the specific conditions under which the concrete is being produced.

The procedure for proportioning mass concrete given in Appendix 5, ACI 211.1 (ACI 1991a) is similar to that for proportioning normal concrete with two significant exceptions. Since mass concrete typically contains more than one size group of coarse aggregate, instructions are provided for combining the coarse aggregates to produce a total coarse aggregate grading that approaches an idealized grading which will result in maximum density and minimum voids. This grading is based approximated by the equation

$$P = \frac{d^x - 0.1875^x}{D^x - 0.1875^x} \ (100) \tag{3}$$

where

P = cumulative percent passing the d-size sieve

d = sieve opening, (millimetre)

D = nominal maximum size aggregate, (millimetre)

x = exponent (0.5 for rounded and 0.8 for crushed aggregate)

Equation 2 is based upon work conducted by Fuller and Thompson (1907) on the packing characteristics of particulate material. The determinations of the 0.5 and 0.8 exponents were made by reviewing the results of numerous dry-rodded weights obtained with various types of coarse aggregate up to 300-mm NMSA (Tynes 1968). The second major difference between the ACI 211.1 (ACI 1991a) methods for proportioning normal and mass concretes involves the use of estimated mortar contents for mass concrete depending on the NMSA be used. Table A5.6, ACI 211.1 (ACI 1991a), of the practice provides estimated mortar

contents for various NMSA and is inserted because large aggregate mixtures require a minimum mortar content for suitable workability.

SeeMIX Mixture-Proportioning Methodology

The seeMIX program, a stand-alone mixture-proportioning and adjustment program developed by Shilstone Software Co., is also incorporated into the SmartPlant program. SmartPlant is designed to enable the concrete producer to automatically assess the variability occurring in both the materials and concrete properties. This program is designed to make appropriate adjustments in the mixture proportions and subsequent batch weights using the incorporated features of seeMIX. SeeMIX provides the user with the capability of proportioning and adjusting mixtures in accordance with the procedures described in ACI 211.1 (ACI 1991a) or by using alternate proportioning methodology recommended by Shilstone Software Co. Shilstone refers to this alternate system of selecting and adjusting concrete mixture proportions as mixture optimization. He suggests that the three principal factors upon which mixture proportions can be optimized for a given need with a given combination of aggregate characteristics include the relationship between the coarseness of the two larger aggregate fractions and the fine aggregate, the total amount of mortar, and the aggregate particle distribution (Shilstone 1990). The primary focus of the Shilstone mixture optimization procedure is the selection of aggregate proportions. He bases the selection of aggregate proportions on the combined aggregate grading within the mixture rather than considering the coarse and fine aggregate gradings separately. In this manner, Shilstone contends that a composite model for the mixture is established which will remain constant as long as aggregate characteristics such as particle shape remain unchanged. If aggregate gradings change within the individual aggregate size groups, adjustments are made as necessary to keep the combined grading constant, and thereby minimize significant changes in the mixture water demand and variations in fresh and hardened concrete properties. In 1991, ASTM C 33 (1991a) made specific provisions for blending coarse aggregate sizes to obtain a desired grading. This provision potentially makes the use of proportioning procedures recommended by Shilstone and contained in seeMIX and SmartPlant more plausible for the concrete industry.

One of the graphical aids used by Shilstone in optimizing mixture proportions is the standard aggregate grading plot. This plot shows the relative balance of the coarse, intermediate, and fine aggregate sizes in the concrete mixture. An example chart is shown in Figure 1. The chart is divided into three segments identified as Q, I, and W, where Q is the percentage of aggregate, by mass, coarser than the 9.5-mm (3/8-in.) sieve; I is the percentage of aggregate, by mass, finer than the 9.5-mm (3/8-in.) sieve but coarser than the 2.36-mm (No. 8) sieve; and W is the percentage of aggregate, by mass, finer than the 2.36-mm (No. 8) sieve. Shilstone states that the portion of the aggregate designated as Q is the high-quality, inert filler sizes and the more of this aggregate that is in the mixture the better, because it will reduce the need for mortar. He states that the portion of aggregate designated as I is the intermediate particles that fill major voids and aid in mixture mobility. If this size range of aggregate is elongated and

sharp, they contribute to harshness of the mixture. He also asserts that at a given consistency, the amount and characteristics of that portion of the aggregate

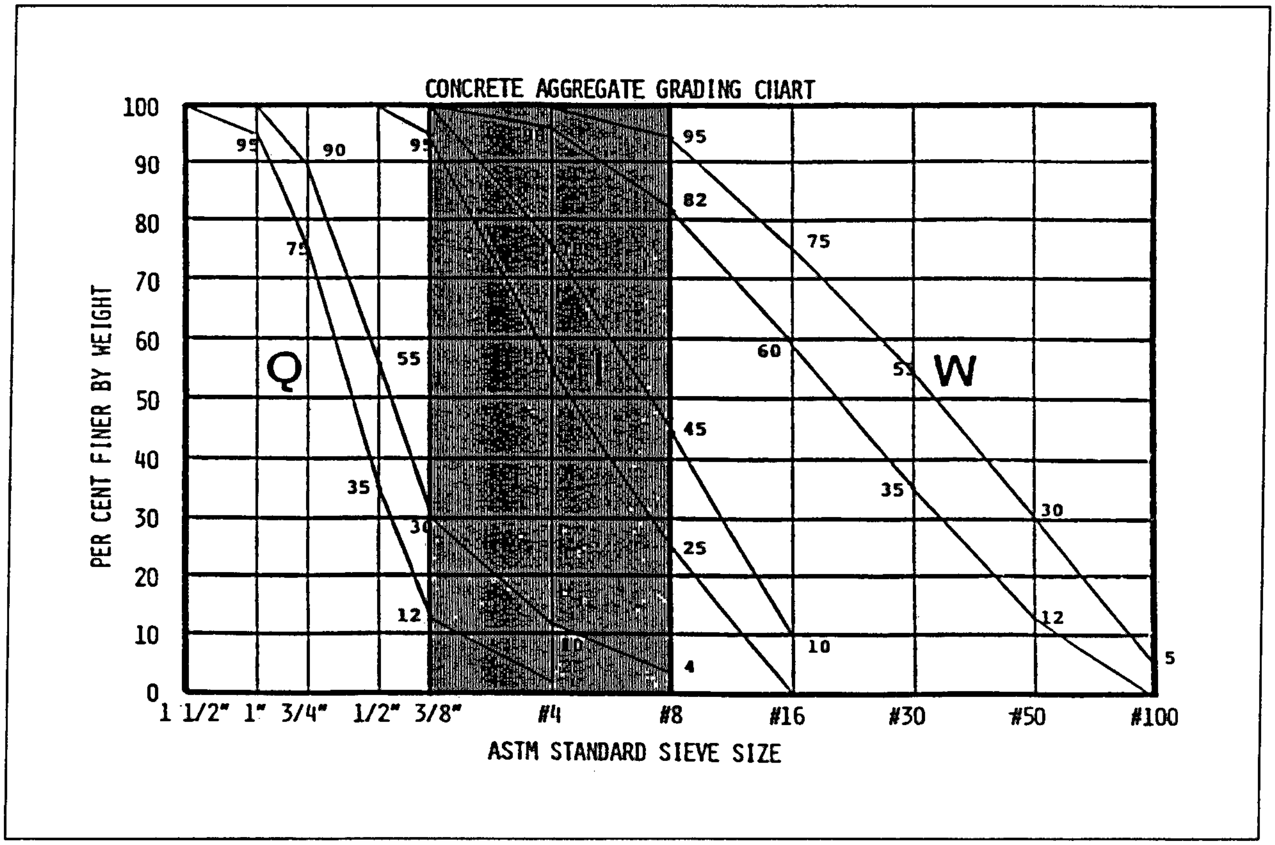


Figure 1. Example of Shilstone Aggregate Grading Chart with divisions of coarse, intermediate, and fine aggregates

designated as *W* significantly influences the workability of the mixture (Shilstone 1990). Based upon his observations of the behavior of concrete mixtures which have been characterized using the Coarseness Factor Chart, Shilstone proposes the following principles (Shilstone 1990):

a. "For every combination of aggregates mixed with a given amount of cementitious materials and cast at a constant consistency, there is an optimum combination which can be cast at the lowest water-cement ratio and produce the highest strength."

b. "The optimum mixture has the least particle interference and responds best to a high frequency, high amplitude vibrator."

c. "The optimum mixture cannot be used for all construction due to variations in placing and finishing need."

Using the Coarseness Factor Chart developed by Shilstone and shown in Figure 2, the relative coarseness of the aggregate larger than the 2.36-mm (No. 8)

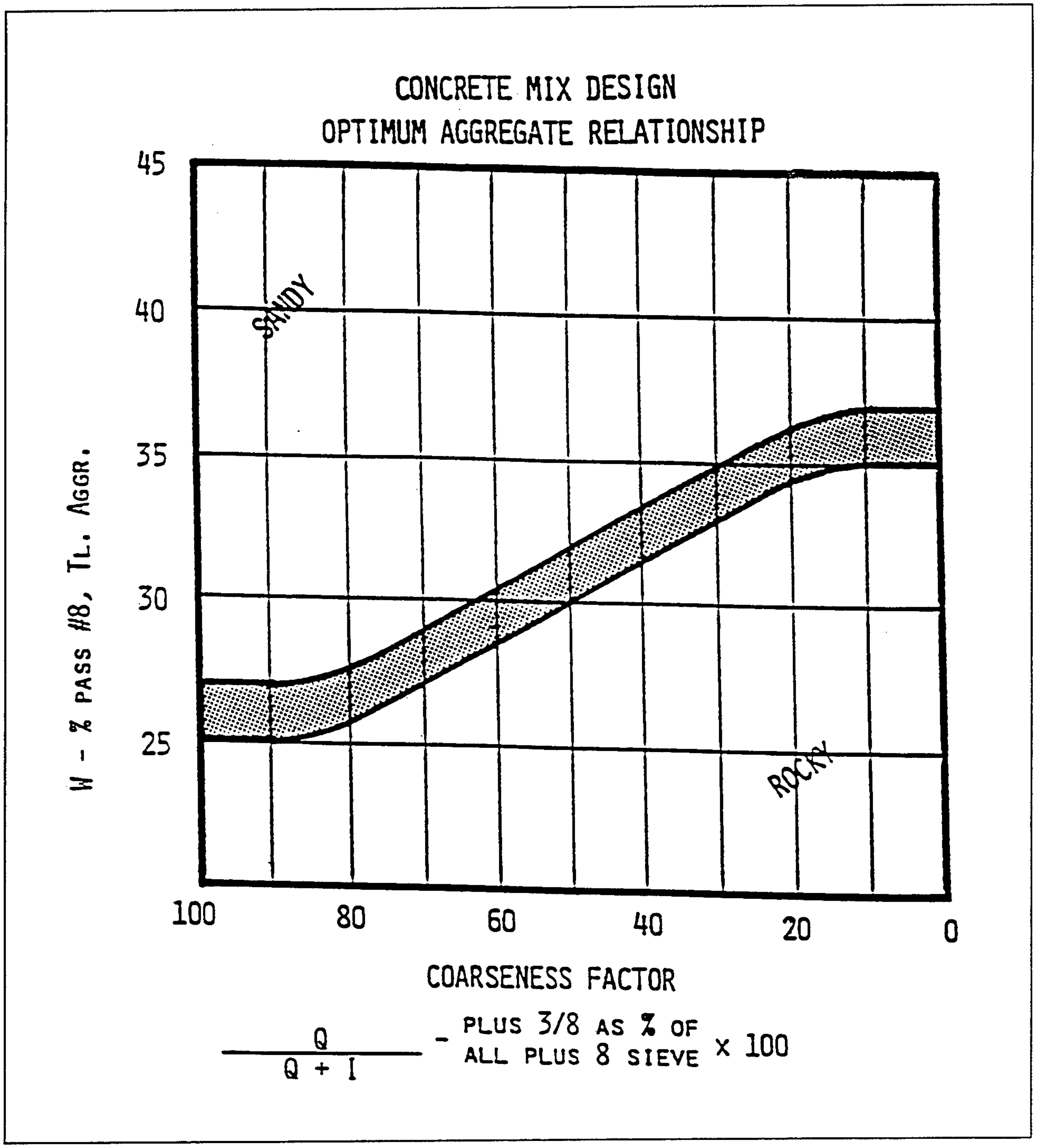


Figure 2. Example of Shilstone Coarseness Factor Chart

sieve is plotted as the abscissa. The relative coarseness is defined as $Q/(Q+I)$. The percentage of aggregate finer than the 2.36-mm (No. 8) sieve, W, is plotted as the ordinate. A second point plotted on the chart represents an adjustment based upon the cementitious material content of the mixture. This adjustment is necessary since the fine aggregate content required in a mixture is influenced by the cementitious material used in the mixture. The base relationship between W and the adjusted workability value, *W-Adj*, is the volume of cementitious material equal to 335 kg/m^3 (564 lb/yd^3) of cement. W and *W-Adj* are identical at this cementitious material content. If the cementitious material content is lower than 335 kg/m^3 (564 lb/yd^3), *W-Adj* will be lower on the chart than W. A trend bar, shown in Figure 1 as the shaded area in the middle portion of the chart, divides the chart into sandy and rocky zones. The trend bar serves only as a reference to assist the user in analyzing aggregate gradings. If the aggregates are well-graded natural sand and gravel or cubical crushed stone, the optimum mixture combined grading can plot in or near the trend bar. Such mixtures generally must be placed by bottom dump bucket or by paving machine, and the water demand for these mixtures will probably be the lowest possible. Shilstone (1990) states that these mixtures will also respond well to a large, high-frequency, high-amplitude vibrator even at a low slump. General use mixtures plot 5 to 6 percentage points above the trend bar, and for a given combination of materials, the user must determine the optimum relationship for varying needs. When variations in aggregate gradings occur, adjustments can be calculated and the new aggregate proportions selected to closely approximate the original mixture.

The mortar factor is an extension of the Coarseness Factor Chart and is a parameter for optimizing mixtures which Shilstone defines as the sum of the volume of aggregate finer than the 2.36-mm (No. 8) sieve and the volume of the paste (Shilstone 1990). He maintains that construction requirements which affect mortar needs should be considered when optimizing a mixture and that there are no fixed mortar factors since they are influenced by aggregate particle shape, texture, and distribution. However, he does suggest mortar factors for 10 classes of construction which result in a mortar factor range of 48 to 66 percent.

The final parameter considered by Shilstone in optimizing mixture proportions is aggregate particle distribution. He contends that the combined grading of all aggregate sizes used in the mixture should be well graded and that the grading of any particular size group making up the aggregate composite is immaterial. Shilstone cites Fuller and Thompson (1907), Abrams (1918), and Bloem (1956) as sources to support this contention. Shilstone adds that the key to assuring an optimized mixture is a combined aggregate grading which has not more than 25 percent retained on any given sieve and not less than 5 percent retained on the 4.75-mm (No.4) or 2.36-mm (No.8) sieves. He also notes that while a combined grading plot which shows the cumulative percent finer for each sieve size is not as definitive as the percent retained on each sieve, a useful guide is a 0.45 power curve that has the form

$$P = (d/D)^{0.45} \tag{4}$$

where

P = cumulative percent finer than the d-size sieve

d = sieve opening, (millimetre)

D = nominal maximum size aggregate, (millimetre)

Using the combined grading plot which shows percent retained on individual sieves, Shilstone classifies three trends in aggregate distribution. These include a jagged and peaked double hump. The double hump shows peaks in both coarse and fine aggregate sizes with a valley located in the intermediate sizes (4.75-mm (No.4) and 2.36-mm (No.8) sieves). This indicates that the mixture is deficient in the intermediate sizes and, according to Shilstone, is characteristic of mixtures which are difficult to pump and finish (Shilstone 1989). Mixtures that contain aggregates which have the peaked distribution curve have a high incidence of intermediate particles and purportedly can be pumped easily and have excellent finishing characteristics. Oftentimes, supplemental aggregate, such as pea gravel, must be added to the original coarse and fine aggregates to achieve the peaked combined grading. This is necessary because when only one coarse and one fine aggregate meeting ASTM C 33 (ASTM 1991a) or other standard grading requirements are combined in a concrete mixture, the double-hump aggregate distribution is typically created. Shilstone emphasizes that this is the reason the provision currently available in ASTM C 33 (ASTM 1991a) for combining aggregates is so important. Mixtures having the jagged aggregate distribution curve are not severely deficient in the intermediate sizes but do exhibit some of the characteristics of the double-hump curve. Figures 3 and 4 provide graphical examples of the double-hump and peaked aggregate distribution trends.

Shilstone's methodology for selecting the original concrete mixture proportions and adjusting these to maintain optimum workability are summarized in the following statements (Shilstone 1990):

a. "The accepted practice of establishing constant mixture proportions by weight contributes to problems arising from variability in aggregates and construction needs."

b. "The method for selecting trial proportions is of minimal importance. Arbitrary means are as efficient as complex procedures. The only meaningful factors are the characteristics of the composite."

c. "Once a composite is identified as fulfilling a need, that combination of materials and adjustment procedures can be translated into a mathematical or graphical model as a mixture design. This should include procedures for making adjustments based upon statistical data and variations in materials and construction needs. A mixture *design* may be adaptable worldwide and used indefinitely as long as aggregate characteristics are similar except for gradation and specific gravity."

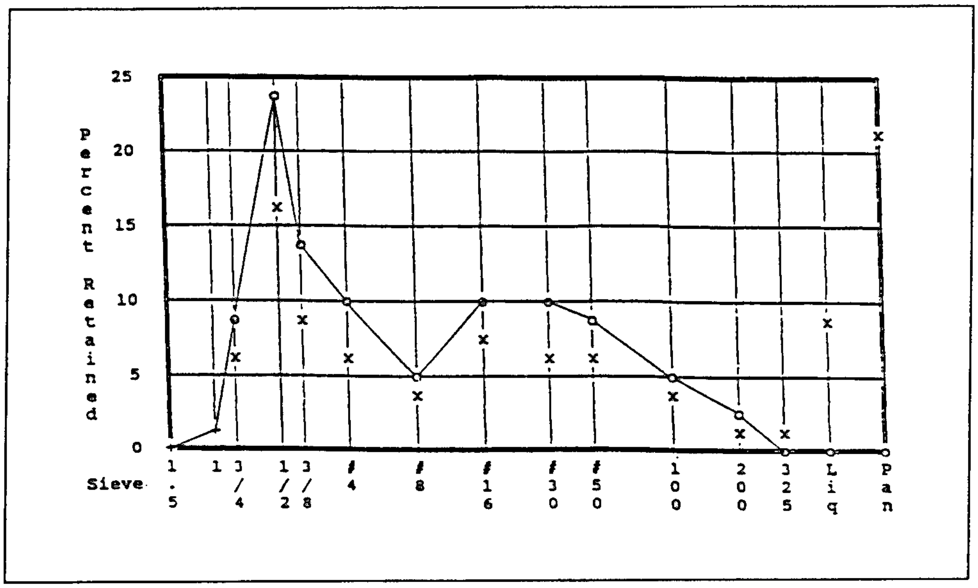


Figure 3. Example of double-hump grading curve

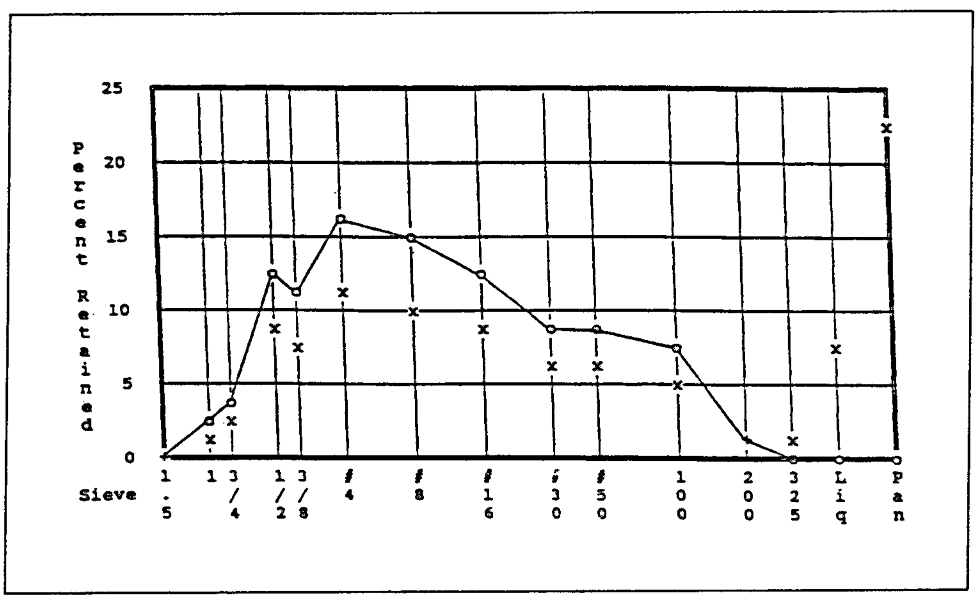


Figure 4. Example of peaked grading curve

d. "Mixture *proportions* are the concrete producer's solution to the *design*, using those sound resources that are available at the lowest price."

e. "Current ASTM and similar aggregate grading limits do not contribute to mixture optimization, as such standards do not address aggregate blends. Aggregates that do not meet ASTM C 33 gradation requirements, but are otherwise acceptable under a quality standard, can be used too with equal ease to produce high quality concrete if they can be controlled to produce a consistent, well-graded composite."

f. "Construction needs are becoming increasingly complex and must be considered second only to engineering criteria when selecting mixture design alternatives."

Objectives of seeMIX Laboratory Evaluation

The objectives of the WES evaluation of the Shilstone Software Co. seeMIX computer program were to determine its effectiveness in proportioning concrete mixtures using the Shilstone mixture optimization parameters discussed in this chapter and to assess whether or not the concrete quality, as determined by laboratory test results, was comparable to that of concrete produced using ACI 211.1 (ACI 1991a).

Scope of seeMIX Laboratory Evaluation

The laboratory evaluation of seeMIX consisted of proportioning structural, paving, and mass concrete mixtures, and evaluating the properties of these mixtures using a number of standardized and nonstandardized fresh and hardened concrete test procedures. Mixtures were proportioned according to the methodology described in ACI 211.1 (ACI 1991a) as well as by procedures recommended by Shilstone and contained in seeMIX for establishing proportions for optimum composite mixtures. Adjustments were made in the mixture proportions as necessary to achieve constant slump and workable mixtures. Fresh and hardened concrete properties measured included slump, air content, unit weight, bleeding, two-point workability, flow under water, compressive strength, flexural strength, abrasion resistance, length change, and rapid chloride ion penetration.

3 Materials, Mixtures, and Test Methods

Materials

Cementitious materials

All of the mixtures proportioned and evaluated in the seeMIX laboratory evaluation contained portland cement, Concrete and Materials Division (CMD) serial no. CPAR-1 C-1, complying with the standard chemical and physical requirements of ASTM C 150 (ASTM 1991g) Type II. The mass and structural concrete mixtures contained fly ash, CMD serial no. WESSC-3 FA-1, meeting the standard physical and chemical requirements of ASTM C 618 (ASTM 1991m), class F. Properties of the cement and fly ash are given in Tables 1 and 2, respectively.

Aggregates

Three coarse and three fine aggregates were used in the laboratory evaluation. The three coarse aggregates consisted of three size groups of crushed limestone having nominal maximum sizes of 75 mm (3 in.), 37.5 mm (1-1/2 in.), and 19.0 mm (3/4 in.), CMD Serial No. CL-2 MG-1, CL-2 MG-2, and CPAR-1 MG-1, respectively. The fine aggregates included a natural siliceous concrete sand, CMD Serial No. WESSC-9 S-2; a manufactured limestone sand, CMD serial no. WESSC-9 MS-2; and a natural siliceous masonry sand, no CMD serial number. The coarse aggregate gradings generally complied with those given for ASTM C 33 (ASTM 1991a) size designations no. 2, no. 4, and no. 67, respectively. The fine aggregate gradings of the natural and manufactured concrete sands complied with the ASTM C 33 (ASTM 1991a) fine grading except that the natural fine aggregate was slightly coarser than allowed by the specification limits on the 2.36-μm (No. 8). The masonry fine aggregate complied with the grading limits given in ASTM C 144 (ASTM 1991f) for natural sand except that it was slightly coarser than allowed by the specification limits on the 300-μm (No. 50) and 150-μm (No. 100) sieves. The coarse and fine

aggregate gradings, absorptions, and bulk specific gravities are given in Tables 3 and 4, respectively.

Table 1
Test Results for Type II Cement, CMD serial no. CPAR-1 C-1

Chemical Analysis	Result	ASTM C 150 Spec. Limits, Type II
SiO_2, percent	22.0	20.0 min
Al_2O_3, percent	3.9	6.0 max
Fe_2O_3, percent	3.0	6.0 max
CaO, percent	62.2	--
MgO, percent	4.1	6.0 max
SO_3, percent	2.7	3.0 max
Loss on ignition, percent	1.1	3.0 max
Insoluble residue, percent	0.15	0.75 max
Na_2O, percent	0.10	--
K_2O, percent	0.88	--
Alkalies-total as Na_2O, percent	0.68[a]	0.60 max
TiO_2, percent	0.22	--
P_2O_5, percent	0.10	--
C_3A, percent	6	--
C_3S, percent	46	--
C_2S, percent	28	--
C_4AF, percent	9	1.5 max
Physical Tests		
Surface area, m^2/kg (air permeability)	356	280 min
Autoclave expansion, percent	0.08	0.80 max
Initial set, min. (Gillmore)	203	60 min
Final set, min. (Gillmore)	285	600 max
Air content, percent	9	12 max
Compressive strength, 3-day, MPA (psi)	19.4 (2,820)	1,500 min
Compressive strength, 7-day, MPA (psi)	25.7 (3,720)	2,500 min
False set (final penetration), percent	100	50 min

[a] Low alkali was not required for this project.

Table 2
Test Results for Fly Ash, CTD Serial No. WESSC-3 FA-1

Chemical Analysis	Result	ASTM C 618 Spec. Limits, Class F
SiO_2	50.6	--
Al_2O_3	30.7	--
Fe_2O_3	6.6	--
Sum	87.9	70.0 min
CaO	1.6	--
MgO	1.1	--
SO_3	0.5	5.0 max
Moisture content	0.2	3.0 max
Loss on ignition	2.1	6.0 max
Available alkalies (28 days)	0.8	1.50 max
Physical Tests		
Fineness (45μm), % retained	13	34 max
Fineness variation, %	--	5 max
Water requirement, %	99	105 max
Density, mg/m^3	2.26	--
Density variation, %	--	5 max
Autoclave expansion, %	0.01	0.8 max
Pozzolanic activity w/lime, MPa (psi)	9.6 (1,390)	6.2 min
Strength activity index, w/cement, 28-day, %	112	75 min

Table 3
Coarse Aggregate Test Results

Sieve Size	Cumulative Percent Finer		
	37.5 - 75 mm (CMD Serial No. CL-2 MG-1)	19.0 - 37.5 mm (CMD Serial No. CL-2 MG-2)	4.75 - 19.0 mm (CMD Serial No. CPAR-1 MG-1)
75 mm (3 in.)	100		
63 mm (2 1/2 in.)	--		
50 mm (2 in.)	45	100	
37.5 mm (1 1/2 in.)	5	96	
25.0 mm (1 in.)		29	100
19.0 mm (3/4 in.)		7	99
12.5 mm (1/2 in.)		3	71
9.5 mm (3/8 in.)		3	48
4.75 mm (No. 4)		2	11
Absorption, percent	0.2	0.3	0.5
Bulk specific gravity	2.72	2.74	2.77

Table 4
Fine Aggregate Test Results

Sieve Size	Cumulative Percent finer		
	150 μm - 4.75 mm (CMD Serial No. WESSC-9 S-2)	150 μm - 4.75 mm (CMD Serial No. WESSC-9 MS-2)	150 μm - 2.36 mm (no CMD Serial No., masonry sand)
9.5 mm (3/8 in.)	100	100	
4.75 mm (No. 4)	99	99	
2.36 mm (No. 8)	79	85	100
1.18 mm (No. 16)	60	50	100
600 μm (No. 30)	46	29	72
300 μm (No. 50)	18	15	4
150 μm (No. 100)	3	6	0
Absorption, percent	1.6	0.9	0.3
Bulk specific Gravity	2.59	2.69	2.60

Admixtures

Air-entraining admixture (AEA), CMD Serial No. CL-60 AEA-1041, was used in all of the mixtures evaluated. The AEA was an aqueous solution containing surface-active agents consisting of fatty acids and salts of sulfonic acids. An evaluation of this AEA in a previous WES investigation indicated that it met the requirements of ASTM C 260 (ASTM 1991k). A water-reducing admixture (WRA), no CTD serial number, was also used in the structural mixtures to improve fresh concrete workability.

Concrete Mixtures

Three categories of mixtures were proportioned and evaluated using guidance provided in the ACI 211.1 (ACI 1991a) and that provided in the Shilstone seeMIX program. The mixture categories included mass, structural, and paving concrete mixtures. Mixtures were proportioned and adjusted so that viable comparisons between fresh and hardened concrete properties could be made. It should be noted that seeMix did not have a provision for aggregate sizes of 75-mm (3 in.). However, for the mass concrete mixtures evaluated in this investigation, an extrapolation of the seeMix methodology was made to include 75-mm (3-in.) NMSA.

Mass concrete

Seven mass concrete mixtures were proportioned during the evaluation, and two batches were produced from each mixture. Each mixture contained 30 percent, by volume of cementitious materials, of Class F fly ash. The w/c, based upon an equivalent volume of cement, of each mixture was 0.55. The desired slump range for each mixture was 37.5 to 63.5 mm (1-1/2 to 2-1/2 in.). The mixture designated MASS-1 was proportioned following the guidelines given in ACI 211.1 (ACI 1991a). This included combining the coarse aggregates in such a manner that the total coarse aggregate grading matched as closely as possible that given in ACI 211.1 for 75-mm (3-in.) NMSA concrete and ensuring that the mortar content of the mixture was approximately 0.44 m^3 (12.0 ft^3). Mixture MASS-2 was similar to the proportions of MASS-1, except that the coarse and fine aggregates were combined such that the total aggregate grading approximated Equation 3, as recommended by Shilstone, as closely as possible. The natural fine aggregate was supplemented with limestone manufactured fine aggregate to approximate the 0.45 power grading curve more closely. Mixture MASS-3 was an adjustment of mixture MASS-2 in which the fine aggregate content was increased to raise the total mortar content to approximately 0.44 m^3 (12.0 ft^3). Mixture MASS-21 was also an adjustment of mixture MASS-2 in which the w/c was maintained at 0.55, and the water and cementitious material contents were increased in an attempt to increase the slump to approximately 50 mm (2 in.). Mixture MASS-31 was an adjustment of mixture MASS-3 in which the w/c was maintained at 0.55 and the water and cementitious materials contents were increased in an attempt to increase the slump to approximately 50 mm (2 in.). The fine aggregate content of this mixture was also reduced to maintain an approximately constant mortar content of 0.44 m^3 (12.0 ft^3). Mixture MASS-32 was a second adjustment of mixture MASS-3 similar to that mixture MASS-31, except that the water and cementitious material contents were increased even more while the fine aggregate content was decreased to maintain the mortar content equal to approximately 0.44 m^3 (12.0 ft^3). Mixture MASS-4 was an adjustment of mixture MASS-2 in which the water, cementitious materials, and fine aggregate contents were increased so that the mortar content of the mixture was increased to approximately 0.48 m^3 (13.0 ft^3). This was done as an alternate means of increasing the slump of mixture MASS-2 to approximately 50 mm (2 in.). The mass concrete mixture proportions are given in Table 5.

Paving concrete

Nine paving concrete mixtures were proportioned during the evaluation, and two batches were produced from each mixture. Each mixture was proportioned for a slump of 25 to 50 mm (1 to 2 in.), and an air content of 5.0 to 6.0 percent. The NMSA of each mixture was 37.5 mm (1-1/2 in.), and no fly ash was used in any of the mixtures. The mixture designated as PAVE-1 was proportioned using practices given in ACI 211.1 (ACI 1991a). The 4.75- to 19.0-mm and 19.0- to 37.5-mm coarse aggregate size groups were combined to closely match the grading given by Equation 2, where 0.8 was selected as the equation exponent.

Table 5
Mass Concrete Mixture Proportions

Mixture	Saturated Surface-Dry Weights, kg/m^3 (lb/yd^3)								
	Portland Cement	Fly Ash	Natural Fine Aggregate	Limestone Fine Aggregate	4.75 - 19.0 mm	19.0 - 37.5 mm	37.5 - 75 mm	Water	w/c
MASS-1	125 (210)	39 (66)	646 (1,090)	0	308 (519)	457 (770)	756 (1,274)	98 (165)	0.55
MASS-2	125 (210)	39 (66)	417 (703)	130 (219)	580 (977)	463 (781)	592 (997)	98 (165)	0.55
MASS-3	125 (210)	39 (66)	517 (872)	98 (165)	539 (908)	426 (718)	560 (943)	98 (165)	0.55
MASS-21	129 (218)	40 (68)	414 (698)	10 (171)	576 (971)	460 (775)	587 (990)	102 (171)	0.55
MASS-31	132 (223)	42 (70)	494 (834)	129 (217)	540 (910)	427 (720)	561 (945)	104 (175)	0.55
MASS-32	136 (229)	43 (72)	491 (829)	128 (215)	537 (905)	425 (716)	557 (939)	107 (180)	5
MASS-4	138 (232)	43 (73)	564 (951)	147 (247)	501 (845)	397 (669)	520 (877)	107 (182)	0.55

This resulted in a combination of 55 percent 37.5-mm NMSA and 45 percent 19.0-mm NMSA. The dry-rodded unit weight of this combination was 1,685 kg/m^3. Table A1.5.3.6, ACI 211.1 (ACI 1991a), therefore recommends 1,171 kg/m^3 of coarse aggregate. Mixture PAVE-2 was similar to PAVE-1, except the aggregates were combined to match the 0.45 power curve recommended by Shilstone. This required the addition of crushed limestone coarse aggregate finer than the 25.0-mm (1-in.) sieve but coarser than the 19.0-mm (3/4-in.) sieve. The water and cementitious contents used in mixture PAVE-2 were the same as those used in PAVE-1. Mixture PAVE-3 was similar to mixture PAVE-2 in that aggregates were graded to closely match the 0.45 power grading curve. However, additional adjustments were made in the mortar content of the mixture to comply with the Shilstone recommended w-adjust and percent mortar factors. Mixture PAVE-4 was similar to mixture PAVE-1 except that the coarse aggregates were separated and recombined such that the combined coarse aggregate grading closely matched the coarse grading limits of aggregate meeting ASTM C 33 (ASTM 1991a) size designation No. 467. Mixture PAVE-5 was similar to PAVE-4 except that the coarse aggregates were separated and recombined such that the combined coarse aggregate grading closely matched the fine grading limits of aggregate meeting ASTM C 33 (ASTM 1991a) size designation No. 467. Mixture PAVE-31 was an adjustment of PAVE-3 in which the w/c was maintained at 0.44, and the water and cement contents were reduced to achieve a slump of 25 to 50 mm (1 to 2 in.). PAVE-41 was an adjustment of mixture PAVE-4 in which the w/c was maintained at 0.44, and the water and cement contents were reduced to decrease the slump to 25 to 50 mm (1 to 2 in.). Mixture PAVE-51 was an adjustment of mixture PAVE-5 made for the same reason as mixture PAVE-41. Mixture PAVE-6 was similar to mixture PAVE-1 except that the coarse aggregate was intentionally gap-graded to evaluate the effects on the fresh and hardened concrete properties. The paving concrete mixture proportions are given in Table 6.

Structural concrete

Five structural mixtures were proportioned during the laboratory evaluation, and two batches were made from each mixture. The structural mixtures were proportioned to achieve a 100- to 125-mm (4- to 5-in.) slump, and a 5.5- to 6.5-percent air content. The mixtures were proportioned with the intention that they would be pumpable using commercial concrete pumping equipment. Each mixture contained 20 percent, by volume of cementitious material, Class F fly ash, and 0.2 ℓ (3.0 fl oz) of WRA/100-kg (100-lb) cementitious material. Mixture PUMP-1 was proportioned in accordance with the practice described in ACI 211.1 (ACI 1991a), and using the guidelines recommended in ACI 304.2R (ACI 1991b). Mixture PUMP-11 was similar to mixture PUMP-1 except masonry sand was added to supplement the natural fine aggregate to more closely match the combined grading recommended in ACI 304.2R (ACI 1991b). Mixture PUMP-2 was similar to mixture PUMP-1 except the aggregates were combined to match the 0.45 power curve grading as closely as possible. Mixture PUMP-21 is an adjustment of mixture PUMP-2 in which the w/c was maintained constant, but the water and cementitious material contents were reduced to reduce the slump to

Table 6
Paving Concrete Mixture Proportions

Mixture	Saturated Surface-Dry Weights, kg/m^3 (lb/yd^3)									
	Portland Cement	Natural Fine Aggregate	4.75 - 19.0 mm	19.0 - 37.5 mm	19.0 - 25.0 mm	12.5 - 19.0 mm	9.5 - 12.5 mm	4.75 - 9.5 mm	Water	w/c
PAVE-1	297 (500)	765 (1,289)	522 (880)	647 (1,091)	0	0	0	0	131 (220)	0.44
PAVE-2	297 (500)	690 (1,163)	741 (1,249)	447 (754)	62 (105)	0	0	0	131 (220)	0.44
PAVE-3	297 (500)	737 (1,243)	711 (1,199)	429 (723)	59 (100)	0	0	0	131 (220)	0.44
PAVE-4	297 (500)	765 (1,289)	105 (177)	631 (1,063)	152 (256)	117 (197)	94 (158)	70 (118)	131 (220)	0.44
PAVE-5	297 (500)	746 (1,257)	261 (440)	333 (561)	71 (120)	202 (340)	131 (220)	190 (321)	131 (220)	0.44
PAVE-31	294 (495)	743 (1,253)	710 (1,198)	429 (723)	59 (100)	0	0	0	129 (218)	0.44
PAVE-41	283 (477)	790 (1,332)	105 (177)	631 (1,064)	152 (256)	117 (197)	94 (158)	70 (118)	125 (210)	0.44
PAVE-51	290 (489)	758 (1,278)	261 (441)	333 (561)	71 (120)	202 (341)	131 (220)	190 (320)	128 (215)	0.44
PAVE-6	297 (500)	746 (1,257)	130 (220)	475 (800)	107 (180)	48 (80)	261 (440)	166 (280)	130 (220)	0.44

100 to 125 mm. Mixture PUMP-3 was proportioned using the percent mortar parameter recommended by Shilstone to determine the mortar content for the mixture. The structural mixture proportions are given in Table 7.

Table 7
Structural Concrete Mixture Proportions

Mixture	Saturated Surface-Dry Weights, kg/m^3 (lb/yd^3)						
	Portland Cement	Fly Ash	Natural Fine Aggregate	Masonry Sand	4.75 - 19.0 mm	Water	w/c
PUMP-1	237 (400)	43 (73)	905 (1,526)	0	968 (1,632)	148 (250)	0.50
PUMP-11	237 (400)	43 (73)	634 (1,068)	218 (368)	1,023 (1,725)	148 (250)	0.50
PUMP-2	237 (400)	43 (73)	885 (1,491)	0	985 (1,660)	148 (250)	0.50
PUMP-21	230 (387)	42 (71)	895 (1,508)	0	996 (1,678)	144 (242)	0.50
PUMP-3	237 (400)	43 (73)	582 (981)	197 (332)	1,101 (1,856)	148 (250)	0.52

Test Methods

Most of the fresh concrete properties measured during the laboratory evaluation of seeMIX were measured following standard ASTM procedures. However, one of the test procedures used to assess flow characteristics of the structural concrete mixtures and one of the test procedures used to assess workability of the mass and paving mixtures were conducted in accordance with procedures outlined in the USACE's *Handbook for Concrete and Cement* (1949). A workability measurement of fresh structural concrete mixtures was conducted using an apparatus and procedures developed by Tattersall (1976). Preparation and testing of hardened specimens followed standard ASTM procedures, except that the determination of the resistance of concrete to chloride ion penetration was conducted on samples from the paving mixtures following American Association of State Highway and Transportation Officials (AASHTO) procedures. The test procedures used and applicable methods are summarized in Table 8. Results and discussion are provided in Chapter 4.

Slump, unit weight, and air content

Slump measurements were performed on samples from replicate batches of all mixtures in accordance with ASTM C 143 (ASTM 1991e). Mass concrete mixtures were wet-sieved over a 37.5-mm (1-1/2-in.) sieve before testing for slump or air content. Unit weight and pressure air content measurements were conducted on samples from replicate batches of all mixtures according to ASTM C 138 (ASTM 1991c) and C 231 (ASTM 1991i), respectively.

Table 8
Summary of Test Methods

Type Test	Concrete Mixture Type	Test Method or Specification
Slump of fresh concrete	M[1], P[2], S[3]	ASTM C 143 (ASTM 1991e)
Unit weight of fresh concrete	M, P, S	ASTM C 138 (ASTM 1991c)
Air content of fresh content	M, P, S	ASTM C 231 (ASTM 1991i)
Bleeding of fresh concrete	M	ASTM C 232 (ASTM 1991j)
Vebe consistency of fresh concrete	M, P	CRD-C 53 (U.S. Army Corps of Engineers 1949b)
Two-point workability of fresh concrete	S	Procedures described by Tattersall (1976)
Flow of concrete under water	S	CRD-C 32 (U.S. Army Corps of Engineers 1949a)
Compressive strength	M, P, S	ASTM C 138 (ASTM 1991d)
Flexural strength	P	ASTM C 78 (ASTM 1991b)
Underwater abrasion resistance	P	ASTM C 1138 (ASTM 1991n)
Chloride ion penetration	P	AASHTO T 277 (AASHTO 1991)

[1] M = Mass concrete mixtures
[2] P = Pump concrete mixtures
[3] S = Structural concrete mixtures

Bleeding

To evaluate the effects of the material proportioning variations on bleeding, measurements were made on fresh concrete samples from replicate batches of the mass mixtures in accordance with ASTM C 232 (ASTM 1991j).

Vebe Consistency

Slump is one measure of the consistency or wetness of a concrete mixture; however, one should not necessarily assume that the higher the slump, the more workable the mixture. If a mixture is too wet, segregation may occur, while one that is too dry may be difficult to place and compact, and segregation may occur due to the tendency for larger particles to roll toward the toe of a pile of deposited concrete. The consistency of the fresh concrete samples from replicate batches of the mass and paving mixtures was also determined using the Vebe test procedures described in CRD-C 53 (USACE 1949b). However, since the mixtures were slumpable, the test procedure was conducted without the 12.5-kg (27.5-lbm) surcharge. The Vebe consistency measurement was conducted to determine how the relatively stiff mass and paving mixtures responded under vibration and to provide an additional assessment of their workability.

Two-point workability

ACI 116R (ACI 1994) defines workability as "that property of freshly mixed concrete or mortar which determines the ease and homogeneity with which it can be mixed, placed, consolidated, and finished." While the definition is straightforward, the property itself is complex and difficult to measure. Tattersall (1976) suggested five factors that affect the workability of concrete:

a. *Time.* The workability of a mixture decreases as time elapses after mixing. The loss of workability is greater in the first few minutes after mixing.

b. *Aggregate properties.* The particle shape, particle size distribution, porosity, and surface texture influence the workability of a mixture. With a given cement and water content, a mixture with a smooth, rounded, large aggregate with a low porosity is more workable than a mixture with a rough, angular, small aggregate with a high porosity.

c. *Cement properties.* The influence of properties upon workability is more important in mixtures with a high cement content. A cement with a high fineness will cause a concrete mixture to lose workability more rapidly than will an ordinary portland cement because of its rapid hydration.

d. *Admixtures.* Most admixtures affect the workability of a mixture even though their main purpose lies elsewhere. On the other hand, the main objective of WRAs is to increase workability while holding water and cement contents constant, or hold workability constant while decreasing water and cement contents. High-range WRAs, or superplasticizers, are so effective that flowing and self-leveling concrete can be produced.

e. *Mixture proportions.* The relative proportions of all constituents affect the workability of the mixture.

Powers (1932) and others have presented theories of the factors affecting the workability of concrete. The attempts to measure workability have been as varied and controversial as the theories of the factors affecting workability. Many test methods have been proposed, yet few have gained acceptance and widespread use. All have been criticized because they are empirical and do not really measure workability. Tattersall (1976) lists 10 tests and discusses the merits and shortcomings of each. A few of these methods have gained enough acceptance to become standardized in the United States or the United Kingdom (e.g., the slump, flow, and compacting factor tests). However, Gerwick, Holland, and Komendant (1981) state, "There is no single test which will provide definitive data on the workability of a concrete mixture."

Some researchers have taken a rheological approach in an attempt to measure workability. If a liquid is confined between two parallel planes, as shown in Figure 5, with one plane moving at a constant velocity due to a constant force, the constant of proportionality between the strain rate and the shear stress, τ, is

defined as the absolute viscosity, η, where *dv/dy* is the velocity gradient, or the rate of shear, γ.

$$\tau = \eta \, dv/dy \tag{5}$$

A liquid that obeys Equation 4 is called Newtonian. The relationship between shear rate and shear stress is graphically shown in Figure 6. Many materials have a minimum stress, or yield value, below which no flow occurs. Materials of this type follow the equation

$$\tau = \tau_o + \mu\gamma \tag{6}$$

where

τ_o = yield value

μ = the plastic viscosity

This model is called a Bingham body, and its behavior is graphically shown in Figure 7. Various researchers have attempted to apply this theory to measuring the properties of freshly mixed concrete using a coaxial cylinder viscometer. Tattersall and Banfill (1983) attempted to overcome some of the problems of the coaxial cylinder viscometer by using a Hobart food mixer fitted with a hook to stir the concrete. A value of torque, in arbitrary units, was obtained by dividing the power required to run the mixer by the speed of the mixer. Torque, T, was then plotted against speed, N, and a linear relationship was discovered. The curves could be represented by the equation

$$T = g + hN \tag{7}$$

where

g = intercept on the torque axis

h = reciprocal of the slope of the line

Since this is the form of Equation 5 for the Bingham model, it is implied that g is a measure of the yield value, τ_o, and h is a measure of the plastic viscosity, μ. Tattersall contended that the workability of concrete can be measured by these two parameters, and Rixom (1978) stated that the g value should be related to the cohesion of the concrete, while the h value is related to the workability. Tattersall and Bloomer (1979) and Bloomer (1979) give mathematical and theoretical justification for g and h being measures of τ_o and μ, respectively. Later models of the machine used by Tattersall used an infinitely variable hydraulic transmission and a 4.75:1 worm-and-pinion right-angled reduction gear. A value for torque was obtained by measuring the oil pressure developed in the hydraulic unit. Experiments have confirmed that the torque is proportional to the pressure developed in the unit.

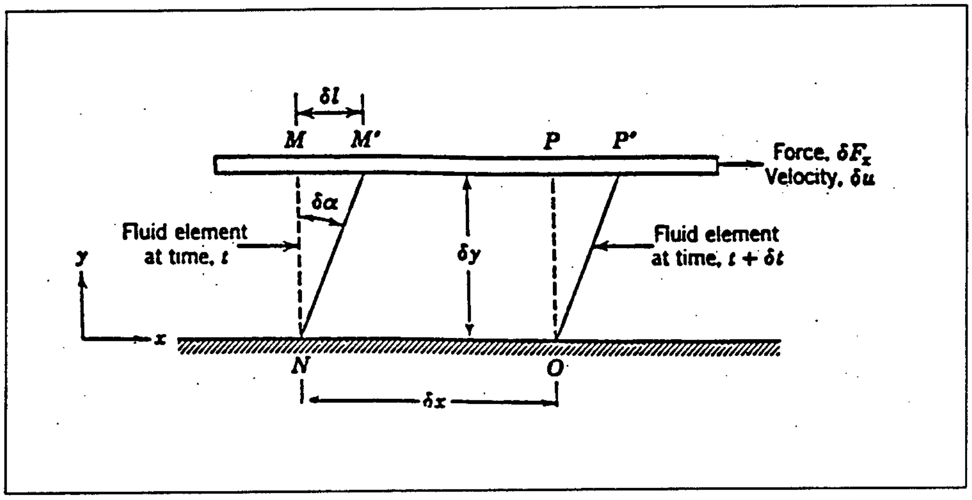


Figure 5. Newton's Law for deformation of a fluid element (Fox and McDonald 1978, reprinted by permission of John Wiley & Sons, Inc.)

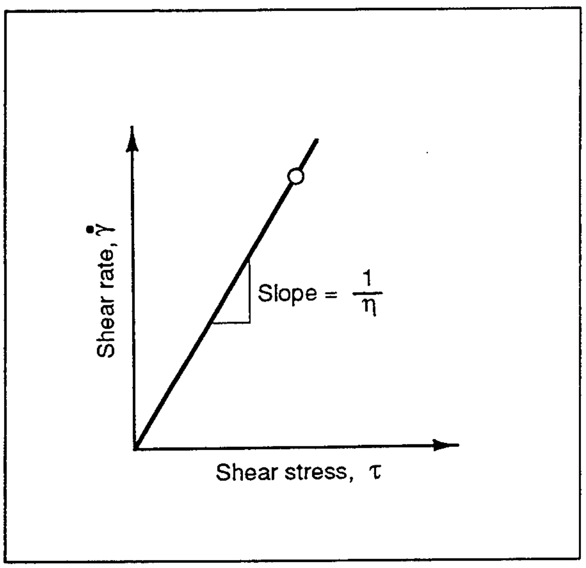


Figure 6. Newtonian liquid: $\tau = \eta\dot{\gamma}$ (after Tattersall and Banfill 1983)

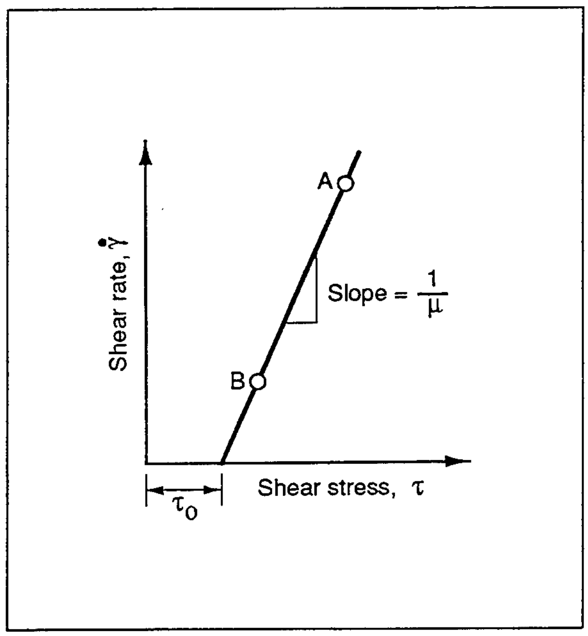


Figure 7. Bingham model: $\tau = \tau_o + \mu\dot{\gamma}$ (after Tattersall and Banfill 1983)

The two-point workability test procedure will measure differences in concrete that are not detected by the slump test. Figures 8, 9, and 10 illustrate the effects of water, high-range water-reducing admixture (HRWRA), aggregate type, and fines content on mixtures having the same slump. Neeley (1988) determined that the two-point workability apparatus was useful for identifying mixtures that are likely to be resistant to washout when placed under water. However, he also confirmed the statement by Gerwick, Holland, and Komendant (1981) that "there

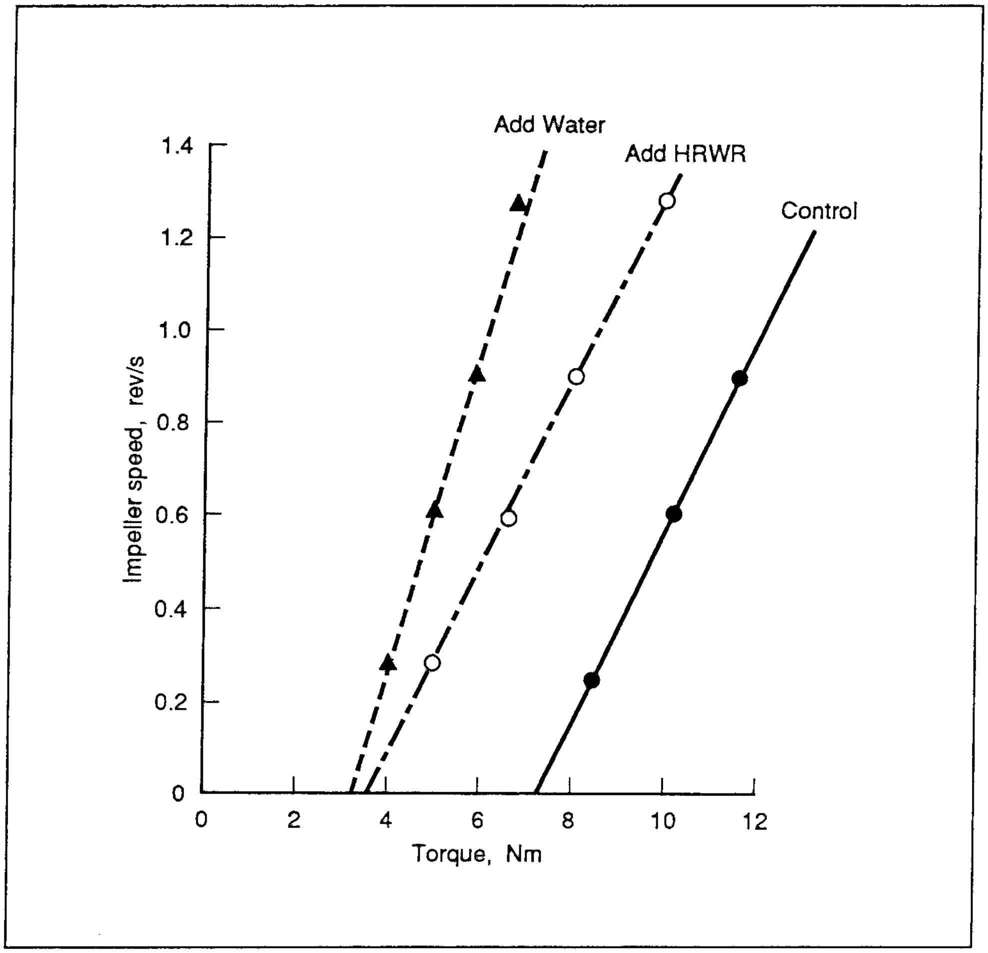


Figure 8. Relative effects of the addition of extra water and of HRWRA (after Tattersall and Banfill 1983)

is no single test which will provide definitive data on the workability of a concrete mixture."

The two-point workability test procedure as described in Appendix A was used to evaluate the workability of samples from replicate batches of the structural mixtures. The standard apparatus will not function properly with stiffer mixtures and consequently was not used to test the mass and paving concrete mixtures. The assembled apparatus is shown in Figure A1.

Flow of concrete underwater

Samples from replicate batches of the structural concrete mixtures were evaluated for flow underwater to assess the effects, if any, of proportioning changes on the flow of the concrete. This test procedure is not a workability test but does provide one with a relative sense of the workability of various mixtures. The measurements were conducted in accordance with procedures described in CRD-C 32 (USACE 1949a).

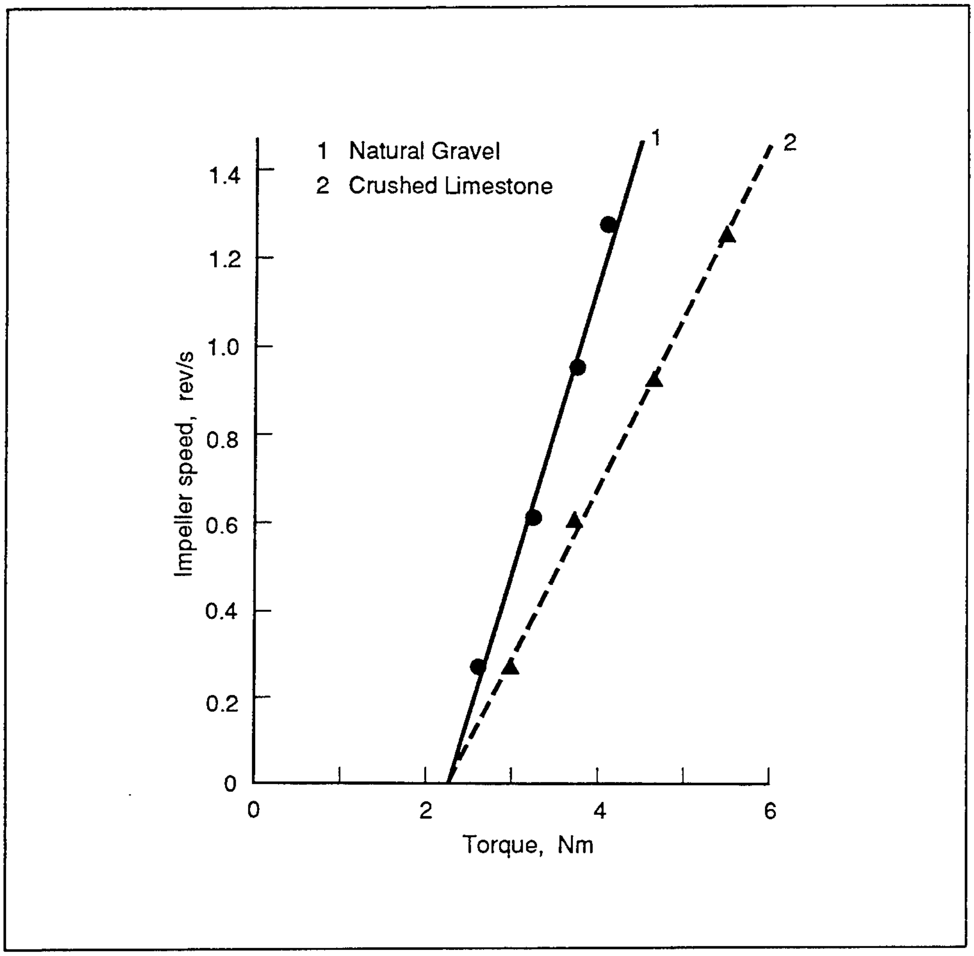


Figure 9. Effects of aggregate type (after Tattersall and Banfill 1983)

Compressive strength

The compressive strengths of specimens representing the replicate batches of each mixture were determined according to ASTM C 138 (ASTM 1991d). Six 152- by 305-mm (6- by 12-in.) cylinders were molded from each batch of concrete. Three each were tested at 28 and 90 days for the mass concrete mixtures, and three each were tested at 7 and 28 days for the paving and structural mixtures.

Flexural strength

The flexural strengths of specimens representing the replicate batches of the paving mixture were determined according ASTM C 78 (ASTM 1991b). Four 152- by 152- by 533-mm (6- by 6- by 21-in.) beams were cast from each batch, and two each were tested at 7 and 28 days.

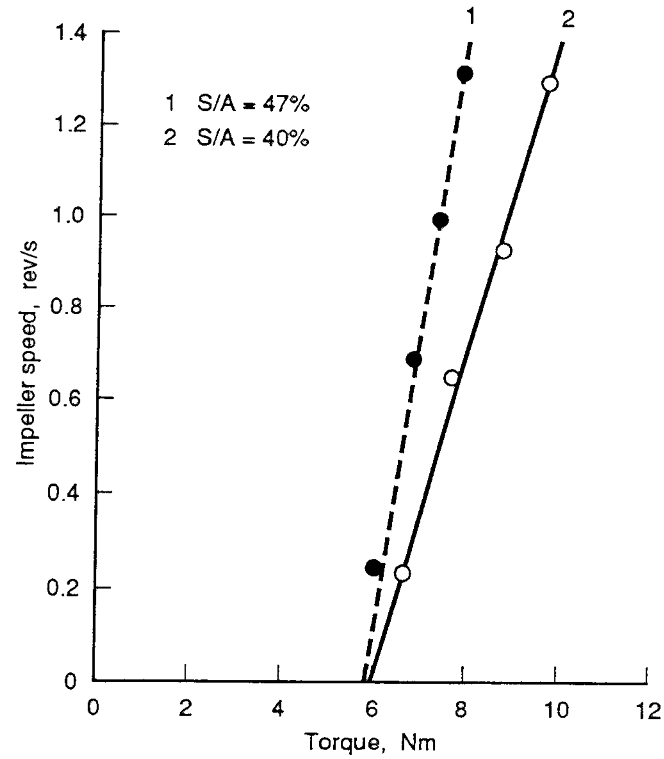


Figure 10. Effects of fines content (after Tattersall and Banfill 1983)

Underwater abrasion resistance

One specimen was cast from samples of replicate batches of the paving mixtures and tested for resistance to underwater abrasion in accordance with ASTM C 1138 (ASTM 1991n). Although this test is not directly related to abrasion experienced by concrete pavements, it does enable one to rank mixtures relative to one another based upon their probable resistance to abrasion. Specimens consisted of 305- by 102-mm (12- by 4-in.) cylinders which were moist cured for 28 days prior to testing.

Resistance to chloride ion penetration

The permeability of a specimen representing each batch of the paving mixtures was estimated following the AASHTO T 277 (AASHTO 1991) test method. In this test procedure, the chloride ion permeability is determined on a preconditioned specimen by measuring the number of coulombs that can pass through a sample in 6 hr. One 102- by 203-mm (4- by 8-in.) cylinder was molded from each batch and moist cured for 28 days. A 50-mm (2-in.)-long sample was then sawed from the top of the cylinder and used as the test specimen.

4 Results of Evaluations

Mass Concrete Results

The primary variations between the mass concrete mixtures included the aggregate gradings and the mortar contents. As noted in Chapter 3, ACI 211.1 (ACI 1991a) provides recommended coarse aggregate gradings and mortar contents for various NMSA. Mixture MASS-1 served as the reference mixture and was proportioned using the ACI 211.1 (ACI 1991a) proportioning guidelines for mass concrete. The remaining mass concrete mixtures were proportioned using a total aggregate grading that closely matched the 0.45 power curve, as recommended by Shilstone. The use of the 0.45 power grading curve required the addition of supplemental fine aggregate as shown in Table 5. SeeMIX does not have provisions for proportioning mass concrete containing 75-mm (3-in.) NMSA; consequently, the *W* and *W-Adj* factors could not be generated automatically. However, the Coarseness Factor Charts and accompanying trend bars were extropolated and manually plotted during the investigation to evaluate these factors. Figure 11 contrasts the combined aggregate grading of mixture MASS-1 and the 0.45 power grading curve. The obvious difference between the two combined gradings centers around the intermediate particle sizes. Conventional mass concrete proportioning practices generally require that these sizes be minimized to reduce the aggregate surface area and the subsequent amount of mortar needed to provide adequate workability. Since lean, mass concrete mixtures by definition have low cementitious material contents, it is essential to minimize the mortar requirements of these mixtures.

Individual test results for slump, air content, unit weight, bleed, Vebe consistency time, and compressive strength are given in Appendix B, Table B1. Table 9 provides a summary of the average fresh concrete test results, compressive strengths, and information regarding the *W* and *W-Adj* factors. The desired slump and air content ranges of the mixtures were 37.5 to 63 mm (1-1/2 to 2-1/2 in.) and 4.5 to 5.5 percent, respectively. The average slump of the reference mass concrete mixture, MASS-1, was at the lower limit of the desired range. However, the mixture was judged to be suitable for bucket placement and one which could be well consolidated using reasonable effort with an internal vibrator. This is validated somewhat by the low average Vebe consistency time

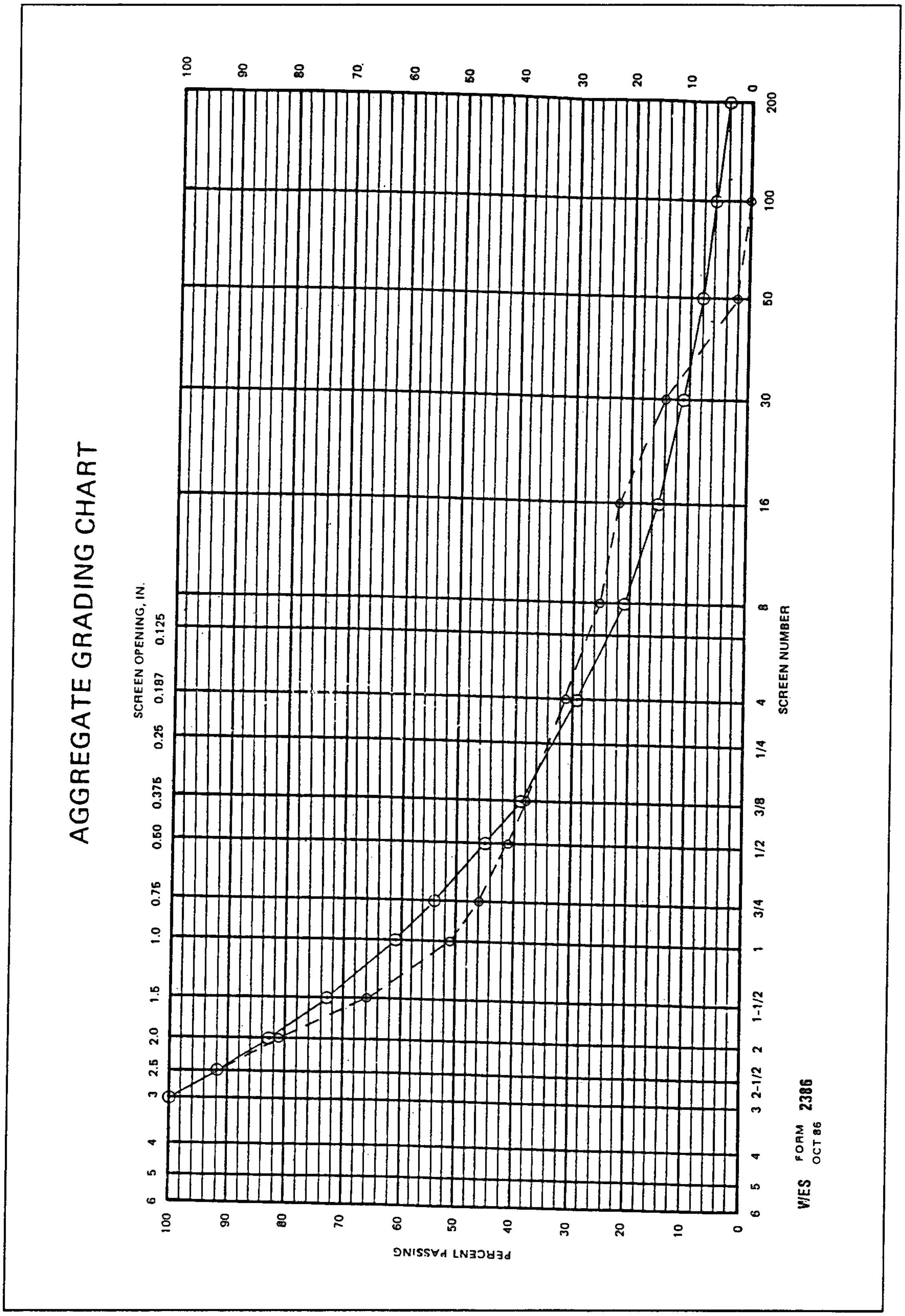


Figure 11. Combined aggregate grading curve of mixture MASS-1 and 0.45 power grading curve

Table 9
Summary of Mass Concrete Test Results

Mixture	Slump mm (in.)	Air Content percent	Unit Weight kg/m^3 (lb/ft^3)	Vebe Consistency sec	Bleed percent	W percent	W-Adj percent	Trend Bar		Compressive Strength MPa (psi)	
								W	W-Adj	28-day	90-day
MASS-1	40 (1-1/2)	5.1	2,350 (146.7)	2.4	3.6	24.5	17.5	-1	-8[a]	20.1 (2,910)	26.7 (3,870)
MASS-2	20 (3/4)	4.4	2,396 (149.6)	7.6	3.5	21.1	14.1	-4	-11	20.1 (2,920)	27.2 (3,940)
MASS-3	10 (1/2)	5.1	2,390 (149.2)	3.9	3.7	24.9	17.9	-1	-8	17.0 (2,460)	23.9 (3,460)
MASS-21	20 (3/4)	5.1	2,364 (147.6)	4.3	4.9	21.1	14.4	-4	-11	18.6 (2,700)	21.4 (3,110)
MASS-31	20 (3/4)	4.3	2,388 (149.1)	3.8	5.3	24.9	18.4	-1	-8	19.9 (2,880)	21.0 (3,050)
MASS-32	40 (1-1/2)	5.3	2,252 (146.8)	3.6	5.4	27.8	21.7	0	-4	19.9 (2,890)	26.2 (3,800)
MASS-4	40 (1-1/2)	4.7	2,368 (147.8)	3.5	5.6	24.9	18.6	-1	-7	9.0 (2,750)	25.2 (3,660)

[a] Indicates percentage points above or below Coarseness Factor Chart trend bar.

experienced by the mixture. The percent bleed of MASS-1 is not particularly high considering that the mixture only has an equivalent cement content, by volume, of 178 kg/m^3 (300 lb/yd^3). The *W* factor falls just below the trend bar in the Shilstone Coarseness Factor Chart; however, the *W-Adj* factor falls eight points below the trend bar. This indicates that the mixture is much leaner than the 335 kg/m^3 (564 lb/yd^3) of cement recommended by Shilstone and, based upon its location on the Coarseness Factor Chart, indicates that this mixture would be considered harsh and rocky, and probably unworkable. Figure C1, Appendix C, shows the *W* and *W-Adj* factors plotted along with the trend bar on the Coarseness Factor Chart.

Mixture MASS-2 reflects an adjustment of MASS-1 such that the combined aggregate grading closely matches the 0.45 power curve. The cementitious materials and water contents remained constant. This resulted in a reduction of the mortar content from approximately 0.44 to 0.40 m^3 (12.0 to 10.9 ft^3). This mixture adjustment reduced the slump of the mixture from 40 to 20 mm (1-1/2 to 3/4 in.). The Vebe consistency time also increased significantly, indicating the mixture was more difficult to consolidate. The bleed was essentially unchanged, and the unit weight of the mixture increased somewhat as a result of replacing a portion of the natural siliceous sand with higher specific gravity limestone coarse and fine aggregate. Both the *W* and *W-Adj* factors were further away from the Coarseness Factor Chart trend bar than the MASS-1 factors. Figure C2 shows the factors for the MASS-2 mixture on the Coarseness Factor Chart. Based upon the fresh concrete test results, this mixture is less workable than mixture MASS-1, and visual observations confirmed this assumption.

Mixture MASS-3 (Figure C3) was an adjustment of mixture MASS-2 in which the fine aggregate content was increased to increase the mortar content of the mixture to approximately 0.44 m^3 (12.0 ft^3). This adjustment actually reduced the average slump slightly, but the Vebe consistency time did reduce significantly indicating that the mixture was easier to consolidate than MASS-2. The bleed percentage remained essentially unchanged, and the unit weight was slightly less than that of mixture MASS-2 because of the addition of more natural siliceous fine aggregate. The *W* and *W-Adj* factors moved closer to the Coarseness Factor Chart trend bar, as shown in Figure C3.

Mixture MASS-21 (Figure C4) was proportioned as an adjustment of mixture MASS-2 in an attempt to increase the slump to 40 to 65 mm (1-1/2 to 2-1/2 in.). Both the water and cementitious materials contents of the mixture were increased, while the w/c was maintained constant. The average slump of the mixture did not change; however, the average Vebe consistency time was reduced. The average percent bleed was greater than that of mixture MASS-2, probably as a result of the increase in water content. The unit weight of the mixture was less than that of mixture MASS-2 due to the increase in water. The *W* and *W-Adj* factors were the same distance from the Coarseness Factor Chart trend bar as those of mixture MASS-2, and a visible evaluation of the mixture indicated that it was grainy and obviously deficient in mortar. The *W* and *W-Adj* factors are plotted on the Coarseness Factor Chart in Figure C4.

Mixture MASS-31 was an adjustment of mixture MASS-3 in which the water and cementitious materials contents were adjusted in an effort to increase the slump to 40 to 65 mm (1-1/2 to 2-1/2 in.). The fine aggregate content was reduced slightly to maintain the mortar content close to 0.44 m^3 (12.0 ft^3). The adjustment did not result in a significant increase in the average slump of the mixture, and the average Vebe consistency time remained effectively unchanged. The average percent bleed increased by approximately 1.5 percent as a result of the higher water content. The *W* and *W-Adj* factors were the same distance from the Coarseness Factor Chart trend bar as shown in Figure C5. Even though this mixture had approximately 0.44 m^3 (12.0 ft^3) of mortar, it visually appeared grainy and deficient in mortar.

Mixture MASS-32 was a second attempt at adjusting mixture MASS-3 to achieve a slump of 40 to 65 mm (1-1/2 to 2-1/2 in.) while maintaining the w/c constant. This increase in water and cementitious materials contents did increase the average slump of the mixture to 40 mm (1-1/2 in.), but reduced the Vebe consistency time only slightly. The average percent bleed of the mixture was greater than either mixture MASS-3 or MASS-31, due to the higher water content. The *W* and *W-Adj* factors (Figure C6) were approximately the same distance from the Coarseness Factor Chart trend bar as those of mixtures MASS-3 and MASS-31.

Mixture MASS-4 increased the mortar content of mixture MASS-2 to approximately 0.48 m^3 (13.0 ft^3) to determine if the workability of the mixture would significantly improve. Although the average slump of the mixture was the same as mixture MASS-1, the average Vebe consistency time was slightly greater, and the percent bleed was almost 2.0 percent greater. The *W* factor actually fell within the Coarseness Factor Chart trend bar, and the *W-Adj* factor was 4 percentage points below the bar. These factors are graphically presented in Figure C7. As a result of the higher mortar content in mixture MASS-4, it was the most workable of the six mixtures proportioned to match the 0.45 power grading curve. However, based upon visual observation, it was not judged to be more workable than mixture MASS-1.

The average compressive strength test results given in Table 9 indicate that both the 28- and 90-day compressive strengths of mixture MASS-1 are generally comparable to or greater than the six mixtures which were proportioned to closely match the 0.45 power combined aggregate grading curve. The strength gain between 28- and 90-days age ranges from 30 to 40 percent for all mixtures except mixtures MASS-21 and MASS-31, which only have strength gains of approximately 15 and 5 percent, respectively. The reason for this is not obvious, since the w/c and the percentage of fly ash, by volume of cementitious material, remained constant. Using compressive strength as one measure of quality, there appear to be little, if any, beneficial effects achieved by recombining the aggregates to closely match the 0.45 power grading curve.

Paving Concrete Results

Results of fresh property measurements

Differences in the paving mixtures primarily centered around the aggregate gradings which were used. Mixture PAVE-1 served as the reference mixture for all of the paving mixtures and was proportioned using the ACI 211.1 (ACI 1991a) proportioning guidelines. The coarse aggregate grading of this mixture also fell in the midrange of the ASTM C 33 (ASTM 1991a) size designation No. 467. Mixtures PAVE-4, -5, -41, -51, and -6 were proportioned such that the coarse aggregate grading approached either the coarse or fine limits of the No. 467 size designation, or was gap-graded within the No. 467 size grading limits. These variations permitted the effects of coarse aggregate grading on fresh and hardened concrete properties to be investigated. Three of the mixtures were proportioned using the seeMIX program. One of these was similar to mixture PAVE-1 except that the combined grading was adjusted to closely match the 0.45 power grading curve, and the remaining two were similar to this mixture except that the *W-Adj* and percent mortar factors were adjusted to comply with Shilstone recommendations. Combined gradings generated by the seeMIX program for each of the mixtures are graphically presented in Figures D1 through D9, Appendix D. Aggregate particle distributions for each mixture are presented in Figure D10 through D18.

Individual paving mixture test results for slump, air content, unit weight, bleed, and Vebe consistency time are given in Table B2, Appendix B. Table 10 provides a summary of the average fresh concrete test results and presents information regarding the *W*, *W-Adj*, and mortar factors. The desired slump and air content ranges of the mixtures was 25 to 50 mm (1 to 2 in.) and 5.0 to 6.0 percent, respectively. The average slump and Vebe consistency time and visual observations of mixture PAVE-1 indicate it was well-proportioned and workable. In addition, very little bleed water was associated with the mixture. The *W* and *W-Adj* factors plotted just above the Shilstone Coarseness Factor Chart trend bar, as shown in Figure C8, which would indicate the proportions of the mixture are near optimum (Shilstone 1990). The 51.7-percent mortar factor slightly exceeds the 48- to 50-percent mortar recommended by Shilstone (1990) for mixtures placed with paving equipment.

Mixture PAVE-2 reflects an adjustment of PAVE-1 such that the combined aggregate grading closely matches the 0.45 power grading curve. This was accomplished by reducing the fine aggregate and 19.0- to 37.5-mm (3/4- to 1-1/2-in.) coarse aggregate contents and increasing the 4.75- to 19.0-mm (No. 4 to 3/4-in.) coarse aggregate content. In addition, approximately 59 kg/m^3 (100 lb/yd^3) of 19.0- to 25.0-mm (3/4- to 1-in.) coarse aggregate was added. The average slump and Vebe consistency time were very similar to those of PAVE-1, indicating the mixture had approximately the same workability. The percent bleed experienced by mixture PAVE-2 was also very close to that of mixture PAVE-1. Both the *W* and *W-Adj* factors fell within the lower portion of the Coarseness

Table 10
Summary of Fresh Paving Concrete Test Results

Mixture	Slump mm (in.)	Air Content percent	Unit Weight kg/m^3 (lb/cu ft^3)	Vebe Consistency Time, sec	Bleed percent	Mortar Factor percent	W percent	W-Adj percent	Trend Bar	
									W	W-Adj
PAVE-1	45 (1-3/4)	5.4	2,364 (147.6)	2.9	1.4	51.7	32.9	31.2	+2	+1[a]
PAVE-2	40 (1-1/2)	5.0	2,382 (148.7)	3.1	1.6	49.6	30.0	28.3	0	0
PAVE-3	55 (2-1/4)	5.9	2,352 (146.8)	1.9	1.3	51.0	32.0	30.3	+1	0
PAVE-4	85 (3-1/4)	5.6	2,348 (146.6)	3.2	1.1	51.3	32.4	30.7	+2	+1
PAVE-5	65 (2-1/2)	6.0	2,345 (146.4)	2.2	1.7	50.7	31.6	29.9	0	0
PAVE-31	45 (1-3/4)	5.7	2,352 (146.8)	1.9	1.6	51.0	32.1	30.3	+1	0
PAVE-41	30 (1-1/4)	4.9	2,368 (147.8)	2.2	1.6	51.1	33.0	30.7	+3	+2
PAVE-51	40 (1-1/2)	5.6	2,345 (146.4)	2.3	1.4	50.6	31.9	29.9	+1	0
PAVE-6	45 (1-3/4)	5.4	2,348 (146.6)	1.8	2.7	51.6	32.8	31.1	+2	+1

[a] Indicates percentage points above or below Coarseness Factor Chart trend bar.

Factor Chart trend bar, as shown in Figure C9. The mortar factor was also within the range recommended by Shilstone (1990) for paving mixtures.

Mixture PAVE-3 was similar to mixture PAVE-2 except the fine aggregate content was increased in order to increase the mortar and *W-Adj* factors slightly. The average slump of PAVE-3 is greater and Vebe consistency time lower than those of mixture PAVE-2. This may be due, in part, to the fact that the average air content of PAVE-3 is approximately 1 percent greater than that of PAVE-2. The percent bleed in the PAVE-3 mixture is only slightly less than that of mixture PAVE-2. The *W* factor fell slightly above the Coarseness Factor Chart trend bar, while the *W-Adj* fell within the mid-range of the bar. Figure C10 presents the Coarseness Factor Chart for mixture PAVE-3. The mortar factor of PAVE-3 was 1 percentage point greater than the approximate range recommended by Shilstone (1990) for paving mixtures.

Mixture PAVE-4 was similar to mixture PAVE-1 except that the coarse aggregates were separated and recombined such that the combined coarse aggregate grading closely matched the coarse grading limits of ASTM C 33 (ASTM 1991a) size designation No. 467. The result of this adjustment was a significant increase in the average slump and decrease in average Vebe consistency time. The average percent bleed in the mixture was also reduced slightly compared to that of mixture PAVE-1. Both the *W* and *W-Adj* factors fell slightly above the Coarseness Factor Chart trend bar, as shown in Figure C11, and the mortar factor was 1.3 percent greater than the upper range recommended by Shilstone (1990) for paving mixtures. Consequently, this mixture would be considered workable, but perhaps only slightly oversanded.

Mixture PAVE-5 was similar to mixture PAVE-4 except the coarse aggregates were separated and recombined such that the combined coarse aggregate grading closely matched the fine grading limits of ASTM C 33 (ASTM 1991a) size designation No. 467. This caused an increase in the average slump and a reduction in average Vebe consistency time compared to those of mixture PAVE-1. The average air content of mixture PAVE-5 was 6.0 percent, which may have partially accounted for the higher slump and lower Vebe time. The bleed of the mixture was essentially the same as that of PAVE-1. The *W* and *W-Adj* factors fell within the mid to upper portion of the Coarseness Factor Chart trend bar. This is shown in Figure C12. The mortar content was only slightly greater than that recommended by Shilstone (1990) for mixtures placed with paving equipment.

Mixtures PAVE-31, -41, and -51 were adjustments to mixtures PAVE-3, -4, and -5, respectively, and were made to achieve an average slump of 25 to 50 mm (1 to 2 in.). The w/c of each mixture was maintained constant, while the water and cementitious materials contents were appropriately reduced. The result of the adjustment in each mixture was a reduction in average slump, but there was no change in average Vebe consistency time. The average percent bleed of the adjusted mixtures also remained essentially unchanged. The *W*, *W-Adj*, and mortar factors of mixture PAVE-31, -41, and -51 also remained approximately the same as those of mixtures PAVE-3, -4, and -5. The *W* and *W-Adj* for the

mixtures are plotted on the Coarseness Factor Charts in Figures C13 through C15.

Mixture PAVE-6 was similar to mixtures PAVE-4 and -5 except that the coarse aggregates were separated and recombined such that the combined coarse aggregate grading was gap-graded within the grading limits of ASTM C 33 (ASTM 1991a) size designation No. 467. Unlike mixtures PAVE-4 and -5, no reduction in water and cementitious materials content was necessary to achieve the desired average slump, indicating this mixture had a slightly higher water demand than PAVE-4 and -5. The average Vebe consistency time was approximately the same as mixtures PAVE-4 and 5, but the percent bleed was approximately 1 to 1.5 percent greater. The *W* and *W-Adj* factors fell only a few percentage points above the trend bar of the Coarseness Factor Chart, as shown in Figure C16, and the mortar factor was approximately 1.5 percent greater than the maximum recommended by Shilstone (1990) for paving mixtures.

Results of hardened property measurements

Individual paving mixture test results for compressive and flexural strength and for chloride ion penetration resistance are given in Table B3, Appendix B. Table B4 provides the results of individual underwater abrasion tests. Table 11 provides a summary of the average hardened concrete test results for the paving mixtures. Table 12 provides a summary of two-sample t-test statistical analyses of both the compressive and flexural strength data. This summary compares the mean compressive and flexural strength for each mixture at both 7 and 28 days to those of mixture PAVE-1 to determine if the adjustments caused statistically significant changes in strength. The t-tests were conducted at the 0.05 level of significance.

Table 11
Summary of Hardened Paving Concrete Test Results

Mixture	Compressive Strength, MPa		Flexural Strength, MPa (psi)		Chloride Ion Penetration coulombs
	7-day	28-day	7-day	28-day	
PAVE-1	26.3 (3,810)	31.7 (4,590)	4.10 (595)	4.70 (685)	2,522
PAVE-2	23.5 (3,430)	30.5 (4,430)	4.41 (640)	4.95 (720)	2,283
PAVE-3	22.5 (3,260)	28.3 (4,110)	4.55 (660)	4.60 (670)	--[1]
PAVE-4	23.2 (3,370)	30.6 (4,440)	4.05 (590)	5.50 (795)	--
PAVE-5	22.7 (3,290)	29.1 (4,220)	4.35 (630)	4.95 (720)	--
PAVE-31	23.0 (3,330)	29.6 (4,290)	4.15 (605)	5.05 (735)	2,233
PAVE-41	25.0 (3,620)	32.1 (4,650)	4.25 (620)	4.95 (720)	--
PAVE-51	22.8 (3,300)	30.3 (4,400)	4.00 (580)	4.75 (690)	--
PAVE-6	24.6 (3,570)	31.1 (4,510)	4.40 (635)	5.35 (775)	2,515

[1] -- Indicates test not conducted for this mixture.

Table 12
Summary of Paving Concrete Two-Sample t-Tests on Compressive and Flexural Strengths

Mixture	Compressive Strength					
	t	$t_{0.05}$	Significant Difference	t	$t_{0.05}$	Significant Difference
PAVE-2	2.190	2.015	yes (less)[1]	1.481	1.943	no
PAVE-3	3.160	1.943	yes (less)	4.639	2.015	yes (less)
PAVE-4	2.215	1.812	yes (less)	1.401	2.015	no
PAVE-5	3.097	2.015	yes (less)	3.389	1.943	yes (less)
PAVE-31	2.539	1.812	yes (less)	1.821	1.812	yes (less)
PAVE-41	1.057	1.943	no	-0.607	-1.943	no
PAVE-51	2.873	1.943	yes (less)	1.915	1.943	no
PAVE-6	1.391	2.015	no	0.667	1.812	no
Mixture	**Flexural Strength**					
	7-day			28-day		
PAVE-2	-2.673	-1.943	yes (greater)	-0.861	-1.943	no
PAVE-3	-1.238	-2.353	no	0.452	1.943	no
PAVE-4	-0.502	-1.943	no	-1.295	-1.943	no
PAVE-5	-2.310	-1.943	yes (greater)	-0.908	-1.943	no
PAVE-31	-0.339	-2.353	no	-0.919	-1.943	no
PAVE-41	-1.443	-1.943	no	-0.779	-1.943	no
PAVE-51	1.722	1.943	no	-0.128	-1.943	no
PAVE-6	-1.355	-2.353	no	-2.369	-1.943	yes (greater)

[1] "Less" or "greater" indicates significantly less than or greater than the strength of mixture PAVE-1 from a statistical basis.

The mean 7-day compressive strength of mixture PAVE-2 was significantly less than that of PAVE-1, although there was no significant difference between the 28-day strengths of the two mixtures. The mean 7-day flexural strength of mixture PAVE-2 was significantly greater than that of PAVE-1; however, there was no difference in the 28-day flexural strengths of these mixtures.

The mean 7- and 28-day compressive strengths of mixture PAVE-3 were significantly less than those of mixture PAVE-1. The higher average air content of mixture PAVE-3 partially explains some of the strength reduction; however, the reason for a 10 to 15 percent reduction in compressive strength in mixture PAVE-3 is not readily apparent. There was no significant difference between the flexural strengths of the two mixtures at either 7 or 28 days.

The 7-day compressive strength of mixture PAVE-4 was significantly less than that of mixture PAVE-1, but there was no difference in the 28-day strengths. There was no difference in the 7- and 28-day flexural strengths of these mixtures. Both the 7- and 28-day mean compressive strengths of mixture PAVE-5 were significantly less than those of mixture PAVE-1. Again the higher average air content of PAVE-5 may have been partially responsible for the lower strengths of this mixture. However, it is interesting to note that the mean 7-day flexural strength of mixture PAVE-5 is greater than that of PAVE-1. There was no difference in the 28-day flexural strengths of the mixtures.

Mixture PAVE-31 had mean 7- and 28-day compressive strengths which were also significantly less than those of mixture PAVE-1. The average air contents of the mixtures were approximately equal. The major differences in the two mixtures were the slightly lower water and cementitious materials contents of mixture PAVE-31, and mixture PAVE-1 had a great deal more 19.0- to 37.5-mm (3/4- to 1-1/2-in.) coarse aggregate than PAVE-31. There was no significant difference in the mean flexural strengths of the two mixtures at 7- or 28 day ages. There was also no statistically significant difference between the mean 7- and 28-day mean compressive or flexural strengths of mixtures PAVE-41 and PAVE-1.

The mean 7-day compressive strength of mixture PAVE-51 was less than that of PAVE-1; however, there was no difference in the 28-day compressive strengths. There was also no significant difference in the mean 7- and 28-day flexural strengths. No significant differences existed between the mean 7- and 28-day compressive strengths of mixtures PAVE-6 and -1. The mean 28-day flexural strength of PAVE-6 was, however, greater than that of mixture PAVE-1. The reason for this is not obvious, although mixture PAVE-6 did contain more coarse aggregate, which may have resulted in greater aggregate interlock and a greater average flexural strength.

Tests for underwater abrasion resistance were conducted on a single batch each from mixtures PAVE-1, -2, -31, and -6 to gain a relative sense of the abrasion resistance of the mixtures. These mixtures represented both the reference mixture and the mixtures adjusted to conform with proportioning recommendations given in seeMIX. Mixture PAVE-6 was added only to

determine how a gap-graded mixture would perform. Figure 12 presents average underwater abrasion resistance test results for the four mixtures. This figure indicates that the average abrasion resistance of the mixtures is approximately the same until a test duration of approximately 40 hr is attained. After that time, the average material volume loss of mixture PAVE-31 appears less than that of the other mixtures. At a test duration of 72 hr, the test was concluded and mixture PAVE-31 had experienced approximately 10 percent less material volume loss than did the other three mixtures. The reason for the improved underwater abrasion resistance of mixture PAVE-31 as compared to that of the other mixtures tested is not obvious. Underwater abrasion resistance of a mixture is largely a function of the type and quantity of coarse aggregate it contains. All of the mixtures contained limestone coarse aggregate, and the quantity of coarse aggregate in mixtures PAVE-2 and -6 was greater than that of mixture PAVE-31. The grading of mixture PAVE-31 was similar to that of PAVE-2, except PAVE-31 had more fine aggregate to increase its mortar factor. Additional testing of the mixtures is needed to confirm if, in fact, abrasion resistance of a mixture is significantly improved when the aggregates in the mixture are graded to closely match the 0.45 power curve.

Chloride ion penetration tests were conducted on the same mixtures tested for underwater abrasion resistance. The average results given in Table 11 are presented graphically in Figure 13.

This figure shows that mixtures PAVE-2 and -31 resisted chloride ion penetration approximately 10 percent more effectively than did mixtures PAVE-1 and -6. This may be due to the more densely graded aggregates of mixtures PAVE-2 and -31, which closely matched the 0.45 power grading curve. However, qualitatively, all mixtures would be described as having moderate resistance to the penetration of chloride ions.

Structural Concrete Results

Tests conducted on the structural concrete mixtures focused primarily on the fresh concrete. In addition to the standard ASTM slump, unit weight, and air content tests, workability of these mixtures was evaluated using the two-point workability apparatus and by measuring the flow of the concrete underwater. Compressive strength tests were the only hardened concrete tests conducted on the structural mixtures. Individual fresh concrete test results, including the Shilstone workability factors, are given in Table B5. Individual compressive strength test results are presented in Table B6. A summary of the individual fresh concrete test results is given in Table 13. A summary of the Shilstone workability factors is given in Table 14. Combined gradings generated by seeMIX for the structural mixtures are shown in Appendix D, Figures D19 through D22. Aggregate particle distributions are shown in Figures D23 through D26.

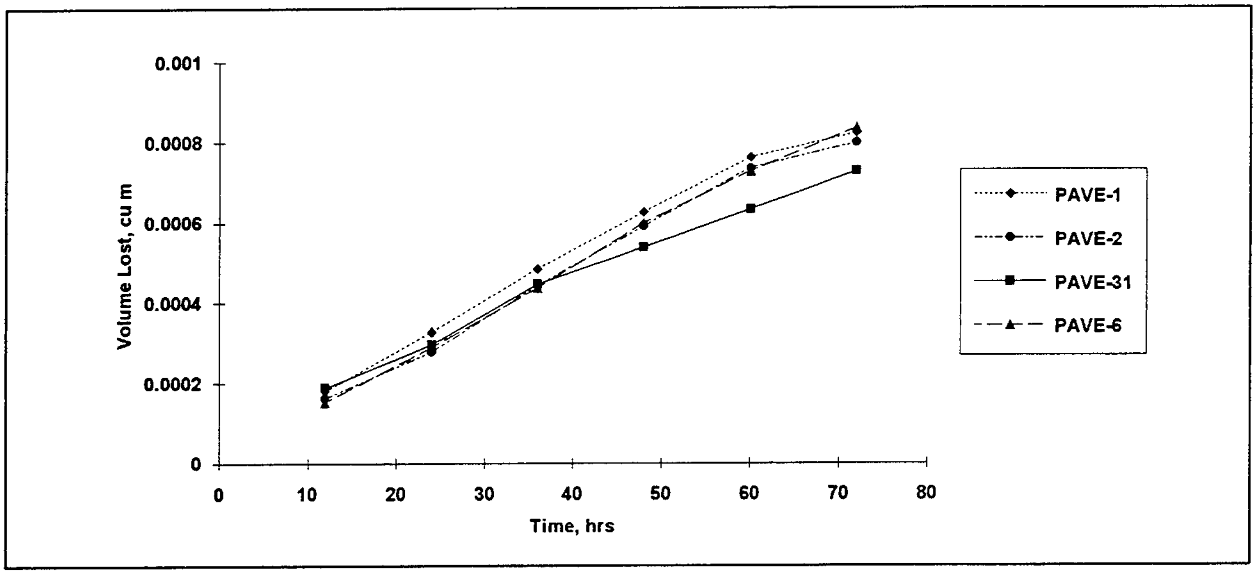


Figure 12. Average underwater abrasion resistance test results for seeMIX laboratory evaluation

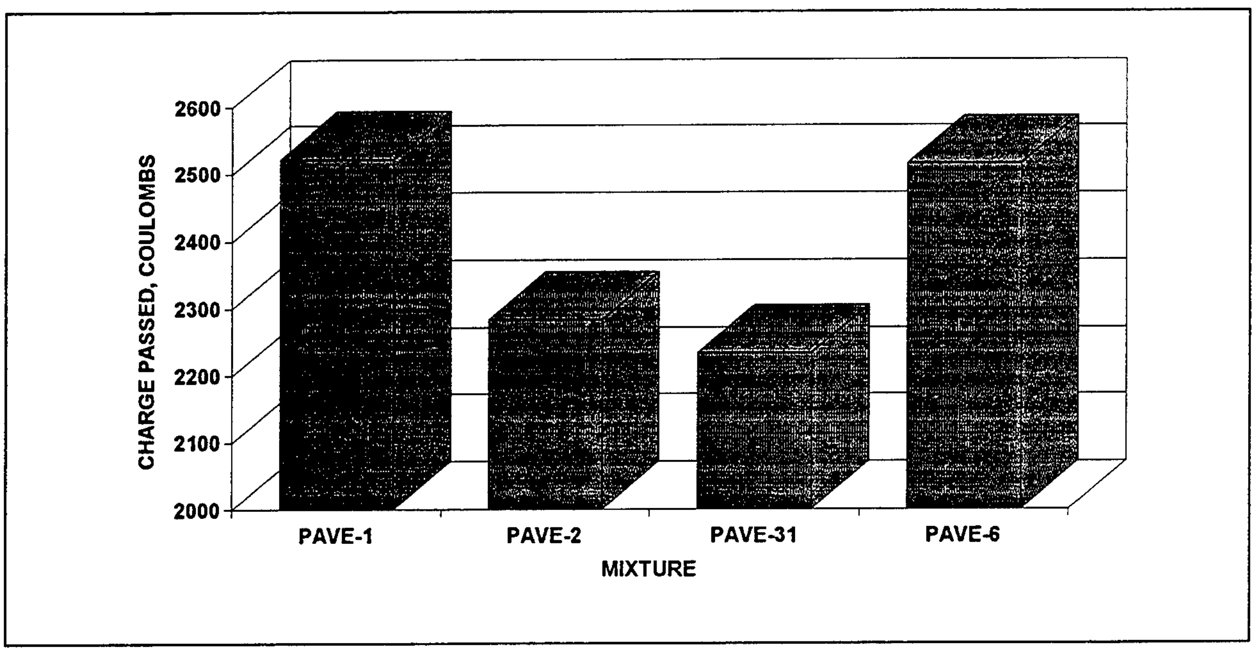


Figure 13. Average chloride ion penetration test results for seeMIX laboratory evaluation

Table 13
Summary of Fresh Structural Concrete Test Results

Mixture	Slump mm (in.)	Unit Weight kg/m^3 (lb/ft^3)	Air Content percent	Bleed percent	Underwater Flow mm (in.)	g	h
PUMP-1	110 (4-1/4)	2,316 (144.6)	5.5	2.2	380 (15)	2.60	0.82
PUMP-11	110 (4-1/4)	2,310 (144.2)	5.6	2.2	375 (14-3/4)	2.18	1.00
PUMP-2	145 (5-3/4)	2,302 (143.7)	5.8	3.0	405 (16)	1.71	0.92
PUMP-21	100 (4)	2,278 (142.2)	6.0	2.0	405 (16)	2.66	0.81
PUMP-3	135 (5-1/4)	2,278 (142.2)	6.0	2.6	405 (16)	1.98	1.00

Table 14
Summary of Shilstone Workability Factors for Structural Mixtures

Mixture	Mortar Factor percent	W percent	W-Adj percent	Trend Bar	
				W	W-Adj
PUMP-1	58.4	40.5	38.1	+6	+4
PUMP-11	58.6	40.7	38.3	+6	+4
PUMP-2	58.0	39.7	37.3	+6	+3
PUMP-21	57.5	39.7	36.9	+6	+3
PUMP-3	56.3	37.3	34.9	+3	+1

Mixture PUMP-1 was proportioned according to guidelines given in ACI 211.1 (ACI 1991a) and ACI 304.2R (ACI 1991b) and served as the reference mixture for those in the structural concrete mixture group.

It contained natural siliceous fine aggregate and a 4.75- to 19.0-mm (No. 4 to 3/4-in.) nominal maximum size crushed limestone coarse aggregate. The ratio of fine-to-coarse aggregate was 0.50, which is higher than would typically be used in a structural concrete mixture. However, the additional fine aggregate was added to increase the mortar content and the potential pumpability of the mixture in accordance with ACI 304.2R (ACI 1991b). The average slump and air content of the mixture were within the desired ranges, although on the lower end of the respective ranges. The *W* and *W-Adj* factors were approximately 4 to 6 percentage points above the Shilstone Coarseness Factor Chart trend bar, as shown in Figure C17. The mortar factor of the mixture was approximately 4 percent greater than the maximum recommended by Shilstone (1990) for concrete placed by a 125-mm (5-in.), or larger, diameter pump line for use in vertical construction, thick flat slabs and larger walls, beams, and similar

elements. Therefore, the *W*, *W-Adj*, and mortar factors would suggest that this mixture probably contained more fine aggregate than was necessary for the intended pumping application. A plot of the average two-point workability torque versus speed data for this mixture is given in Figure E1, Appendix E.

Mixture PUMP-11 was similar to mixture PUMP-1 except that the fine aggregate in the mixture was supplemented with masonry sand to more closely match the recommended grading of ACI 304.2R for pumped concrete mixtures (ACI 1991b). All of the fresh concrete properties of this mixture were essentially the same as those of mixture PUMP-1, except the two-point workability data. Based upon average results of this test, the yield value, *g*, of PUMP-11 was smaller than that of PUMP-1, even though the plastic viscosity was greater. This indicates that mixture PUMP-11 was probably more cohesive and easier to initially mobilize than was mixture PUMP-1 but required more effort to continue moving than did PUMP-1. This is readily apparent by noting the slopes of the torque versus speed curves for the mixtures in Figures E1 and E2. The steeper slope of the mixture PUMP-11 curve indicates that for a given speed of the apparatus shaft, more torque is required. Consequently, a steeper two-point workability speed versus torque curve generally indicates a more workable mixture. In the case of mixtures PUMP-1 and -11, mixture PUMP-1 might be slightly more difficult to begin moving in a concrete pump, but once movement of the concrete through the pumpline begins, it would probably be as easy or easier to continue as would mixture PUMP-11.

PUMP-2 was proportioned such that the combined aggregate grading more closely matched the 0.45 power grading curve than that of PUMP-1. Although the combined aggregate grading curve for PUMP-2 still had a double hump, as viewed in the individual percent retained curve shown in Figure D24, the change apparently improved the workability of the mixture somewhat. The average slump of PUMP-2 was approximately 40 mm (1-1/2 in.) greater than that of mixture PUMP-1. The bleed and underwater flow remained approximately the same. The average *W* and *W-Adj* factors were slightly less than those of mixture PUMP-1, but plotted approximately the same distance above the Coarseness Factor Chart trend bar, as shown in Figure C18. The mortar factors of the two mixtures were also approximately equal. The average two-point workability data illustrated in Figure E3 shows that the cohesion of the mixture, or *g*, was significantly less than that of mixture PUMP-1, and it required only slightly more energy to maintain it in motion than did mixture PUMP-1.

Mixture PUMP-21 was an adjustment of mixture PUMP-2, in which the w/c was maintained constant but the water and cementitious materials contents were reduced to reduce the slump to 100 to 125 mm (4 to 5 in.). This adjustment caused the fresh properties of the mixture to approximate those of mixture PUMP-1. The average slump of the mixture equaled the minimum desired, while the average air content equaled the maximum desired. The average *W* and *W-Adj* factors were approximately equal to those of PUMP-1 and are plotted on the Coarseness Factor Chart trend bar in Figure C19. Figure E4 illustrates that although mixture PUMP-21 contained less cementitious material and water per

cubic yard than did mixture PUMP-1, the average yield value and plastic viscosity were approximately equal.

Mixture PUMP-3 was proportioned using a mortar factor closer in line with that recommended by Shilstone (1990) for pumped concrete using a 127-mm (5-in.)-diam pumpline. The average slump of the mixture was slightly greater than the maximum desired, and the average air content was equal to the maximum desired. The average percent bleed and underwater flow of the mixture were approximately the same as those of mixture PUMP-1. However, the *W* and *W-Adj* factors plotted much closer to the Coarseness Factor Chart trend bar as shown in Figure C20, indicating the mixture was closer to the optimum proportions according to Shilstone than mixture PUMP-1. The mortar factor of PUMP-3 was only approximately 2 percent greater than the maximum recommended by Shilstone (1990) for pumpable concrete. The average two-point workability yield value, g, was less than that of mixture PUMP-1, indicating the mixture was easier to mobilize initially than mixture PUMP-1, but the plastic viscosity of the mixture was slightly greater than that of PUMP-1. This suggests that the mixture might require slightly more energy to keep it in motion than mixture PUMP-1. The average two-point workability test data are shown in Figure E5.

A summary of the structural concrete mixture compressive strength test results is given in Table 15. Analysis of both the 7- and 28-day test results indicates that significant difference, at the 0.05 confidence level, existed at both ages between the strengths of mixture PUMP-1 and any of the other structural mixtures. Although the difference between the average strength of mixture PUMP-1 and any of the other mixtures is significant, it is generally small. However, the within-mixture standard deviation is relatively small for each of the mixtures, and this fact tends to make relatively small strength differences between mixtures statistically significant. The reason for the larger 7- and 28-day compressive strengths of mixture PUMP-1 is not readily obvious based upon the fresh concrete test results, or the mixture proportions.

Table 15
Summary of Structural Mixture Compressive Strength Test Results

	Average Compressive Strength, MPa (psi)	
Mixture	7-day	28-day
PUMP-1	20.6 (2,990)	29.4 (4,270)
PUMP-11	18.6 (2,690)	25.8 (3,740)
PUMP-2	18.3 (2,660)	26.6 (3,860)
PUMP-21	19.5 (2,830)	28.1 (4,070)
PUMP-3	19.0 (2,750)	27.5 (3,990)

5 Field Evaluation of SeeMIX

Blue River Paved Reach

Background

The Blue River Channel Project is a cost-shared effort between the U.S. Government and the city of Kansas City, MO; the design and construction of the project is the responsibility of the U.S. Army Engineer District (USAED), Kansas City. The original project provided for four reservoirs and modification of the Blue River Channel. The construction of the reservoirs was later deleted, and the present project modifies approximately 20.1 km (12.5 miles) of the existing Blue River Channel, commencing near its confluence with the Missouri River and extending upstream to near 63rd Street in Kansas City. The project will provide flood protection against the 30-year flood and will reduce the flooding damage associated with less frequent events. The area protected is predominantly industrial with some small residential areas interspersed. When completed, the project will provide a channel having a bottom width of 30.5 m (100 ft) from the downstream limits of the project upstream to the mouth of Brush Creek.

Construction on the Blue River Channel Project was initiated in 1983 with a contract that widened the channel at the extreme downstream end of the project. Subsequent contracts provided for additional widening and stabilization of the channel and for removing contaminated sediments from a short reach of the channel. A Paved Reach contract awarded by the USAED, Kansas City, was broken into three distinct reaches of construction. In the downstream reach, the channel was widened and the slopes stabilized with riprap. In the middle reach, the channel and slopes were paved with concrete. In this reach, the normal flow of the Blue River will be carried in a precast U-flume which is 4.6 m (15 ft) wide and 1.7 m (5.5 ft) deep. In the remaining reach, the channel is to be widened and the slopes stabilized with a rockfill shell.

The concrete mixture proportions used in the precast sections of the middle portion of the Paved Reach were evaluated and adjusted to assess the effects of seeMIX optimization of the mixture proportions on fresh and hardened mixture properties. Field adjustments and testing of the mixture required close cooperation between the USAED, Kansas City; the precast concrete producer,

Wilson Concrete Co.; WES; and Shilstone Software Co. This work required modification of the contract specifications by the USAED, Kansas City, to provide for the intermediate aggregate sizes recommended by Shilstone to optimize the mixture proportions. This was done to produce precast concrete U-flume sections for the Paved Reach which, it was hoped, would be stronger, more abrasion resistant, and less permeable to deleterious substances. A typical precast U-flume section is shown in Figure 14.

Scope of evaluation

The Blue River evaluation of seeMIX consisted of both field assessments of concrete workability and laboratory testing of fresh and hardened concrete. In June and July 1992, initial assessments of the proposed concrete mixture proportions and those proposed by James Shilstone, Sr., using seeMIX, were made by WES at the Wilson Concrete Co. precast facility in Kansas City, KS. Later in July, materials were sent to WES so that final adjustments to the mixture proportions could be made in the laboratory. Laboratory testing of the originally proposed mixture and the adjusted mixture which was based upon seeMIX concepts was conducted by WES early in 1992. Tests conducted included slump, air content, bleeding, underwater abrasion resistance, resistance to chloride ion penetration, and length change.

Materials and mixtures

An ASTM C 150 (ASTM 1991g), Type I portland cement (CMD serial No. CPAR-3 C-1) was used in the mixtures. Physical and chemical properties of the cement are given in Table 16. Aggregates used consisted of two natural fine aggregates and crushed limestone coarse aggregate. One of the fine aggregates (CMD serial No. CPAR-3 S-1) was graded from the 4.75-mm to 150-μm sieves and was the concrete fine aggregate to be used in the originally proposed mixture. The second fine aggregate (CMD serial No. CPAR-3 S-2) was recommended by Shilstone to provide the intermediate sizes necessary for the combined aggregate grading of the mixture to approach the 0.45 power curve. This aggregate was graded from the 9.5-mm to 600-μm (3/8-in. to No. 30) sieves. The coarse aggregate (CMD serial No. CPAR-3 MG-1) met the requirements of an ASTM C 33 (ASTM 1991a) size designation No. 67, although it was on the fine side of the grading limits. Fine and coarse aggregate gradings, bulk specific gravities, and absorptions are given in Table 17. Admixtures used in the Blue River mixtures included AEA (CMD serial No. CPAR-3 AEA-1), water-reducing and retarding admixture (CMD serial No. CPAR-3 AD-2), and HRWRA (CMD serial No. CPAR-3 AD-3).

The Blue River Paved Reach project specifications required that the mixture achieve a minimum compressive strength of 27.6 MPa (4,000 psi) at 28 days and that the w/c not exceed 0.45. The specifications also required a minimum cementitious materials content of 335 kg/m^3 (564 lb/yd^3). The maximum allowable slump of the mixture was 65 mm (2-1/2 in.), but this was later modified

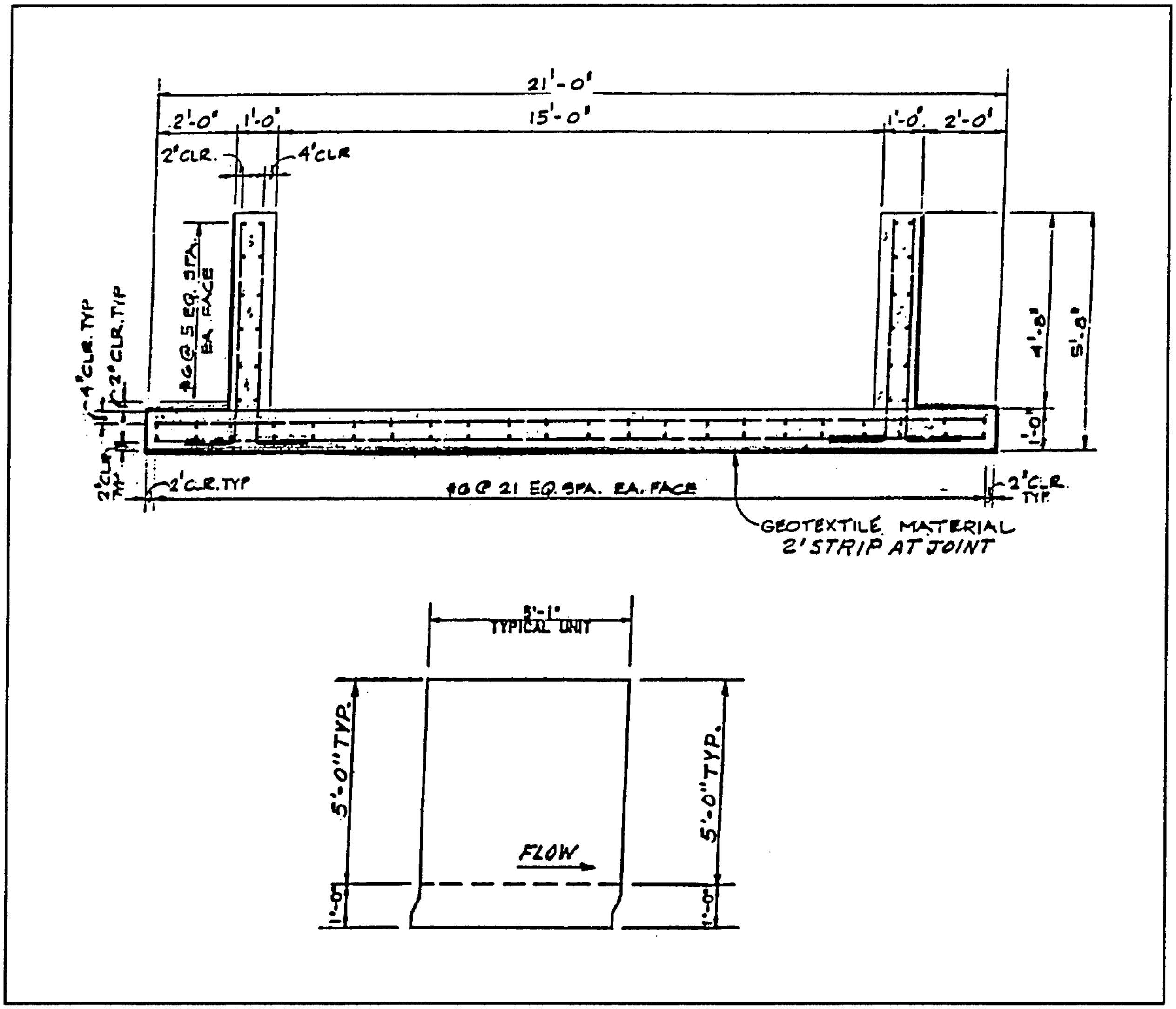


Figure 14. Typical Blue River Paved Reach precast concrete U-flume section

Table 16
Test Results for Blue River Paved Reach Type I Cement, CMD Serial No. CPAR-3 C-1

Chemical Analysis	Result	ASTM C 150 (ASTM 1991g) Spec. Limits, Type II
SiO_2, percent	20.9	20.0 min
Al_2O_3, percent	4.9	6.0 max
Fe_2O_3, percent	2.6	6.0 max
CaO, percent	63.6	--
MgO, percent	2.1	6.0 max
SO_3, percent	3.5	3.0 max
Loss on ignition, percent	0.8	3.0 max
Insoluble residue, percent	0.20	0.75 max
Na_2O, percent	0.17	--
K_2O, percent	0.37	--
Alkalies-total as Na_2O, percent	0.41	0.60 max
TiO_2, percent	0.19	--
P_2O_5, percent	0.12	--
C_3A, percent	10	--
C_3S, percent	51	--
C_2S, percent	22	--
C_4AF, percent	8	1.5 max
Physical Tests		
Surface area, m^2/kg (air permeability)	380	280 min
Autoclave expansion, percent	0.00	0.80 max
Initial set, min. (Gillmore)	165	60 min
Final set, min. (Gillmore)	270	600 max
Air content, percent	9	12 max
Compressive strength, 3-day, MPa (psi)	21.4 (3,100)	10.3 (1,500 min)
Compressive strength, 7-day, MPa (psi)	27.2 (3,940)	17.2 (2,500 min)
False set (final penetration), percent	76	50 min

Table 17
Blue River Paved Reach Aggregate Test Results

Sieve Size	Cumulative Percent finer		
	150 μm - 4.75 mm (CMD Serial No. CPAR-3 S-1)	600 μm - 9.5 mm (CMD Serial No. CPAR-3 S-2)	4.75 mm - 19.0 mm (CMD Serial No. CPAR-3 MG-1)
19.0 mm (3/4 in.)			100
12.5 mm (1/2 in.)			89
9.5 mm (3/8 in.)		100	52
4.75 mm (No. 4)	100	99	3
2.36 mm (No. 8)	90	20	2
1.18 mm (No. 16)	70	3	
600 μm (No. 30)	41	2	
300 μm (No. 50)	12	1	
150 μm (No. 100)	1		
Absorption, percent	0.4	1.6	1.1
Bulk specific gravity	2.62	2.56	2.63

at the request of the contractor to allow for an initial slump of 25 mm (1 in.) and a final slump after the addition of HRWRA of 127 $\pm$ 38 mm (5 $\pm$ 1-1/2 in.). The required air content was 5.0 to 7.0 percent. The mixture originally proposed for use by the precast producer for the precast U-flume sections, mixture BR-1, contained 50 percent, by volume of total aggregate, coarse aggregate. The mixture did not contain the coarser fine aggregate proposed by Shilstone, and consequently the total aggregate grading was not uniformly graded. This is illustrated by the aggregate grading curve of the mixture shown in Figure 15.

Shilstone proposed two mixtures, BR-2 and BR-3, which contained the coarser concrete fine aggregate. This was done to provide the intermediate aggregate sizes that were unavailable in the original mixture and to closely match the 0.45 power grading curve. No additional cement was added to these mixtures. U-flume sections were also cast using these mixtures.

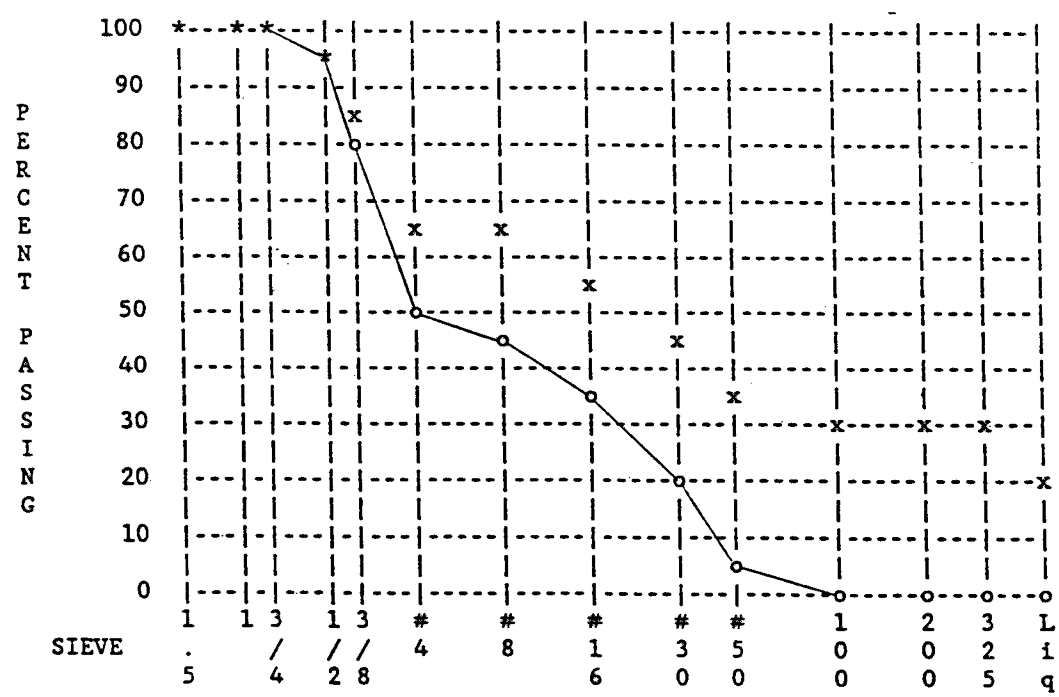
Mixture BR-4 represents a WES adjustment of the proportions of BR-3 in which the quantity of the coarser fine aggregate was reduced and the water and cement contents were increased while maintaining the w/c constant. The adjustment in the aggregates was done to more closely match the 0.45 power

PSI: 4000 PSI Mix: WILSON 07/15/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "				100.0	100.0
1 "				100.0	100.0
3/4 "	100.0			100.0	100.0
1/2 "	90.0			96.5	95.0
3/8 "	57.0			85.0	78.5
# 4	4.0	100.0		66.4	52.0
# 8	3.0	91.0		62.9	47.0
# 16	2.0	72.0		55.9	37.0
# 30	2.0	42.0		45.4	22.0
# 50	2.0	10.0		34.2	6.0
# 100	2.0	1.0		31.1	1.5
# 200	2.0	-	100.0	30.7	1.0
# 325	-	-	94.7	28.4	-
Liquid	-	-	64.7	19.4	-

GRADATION CHART



x - ALL COMPONENTS o - AGGREGATES * - BOTH

Figure 15. Aggregate grading curve for Blue River Paved Reach Mixture BR-1

grading curve advocated by Shilstone. The combined aggregate grading of the mixture is shown in Figure 16. Table 18 summarizes all of the Blue River mixture proportions.

Results and discussion

Mixtures BR-1-4 were observed being batched and placed at the precast producer's facility. Concrete workability and finishing characteristics were visually assessed as U-flume forms were cast. The response of the concrete to internal vibration was carefully noted. Observations of fresh concrete behavior are presented in Table 19. A number of 152- by 305-mm (6- by 12-in.) compressive strength test specimens were made by the concrete producer during production of the trial mixtures. The average 28-day strengths of each of the four mixtures produced were greater than 41.4 MPa (6,000 psi). Although the mixtures had 28-day strengths which were much greater than required by the specifications, they provided the precast concrete producer the flexibility needed to strip forms after only 16 hr when steam curing was used. This permitted increased production, which more than offset the expense of the extra cement.

Three batches each of mixtures BR-1 and -4 were produced and tested at WES. Fresh tests conducted included slump, unit weight, air content, bleeding, and two-point workability. Hardened concrete tests conducted included compressive strength at 7- and 28-days, resistance to underwater abrasion, length change, and resistance to chloride ion penetration. Test methods followed were the same as noted in Chapter 4 of this report.

Individual fresh concrete results of mixtures BR-1 and -4 are given in Table F1, Appendix F. A summary of average fresh concrete test results is presented in Table 20. The average slumps, unit weights, and air contents of the two mixtures were approximately equal. However, the average percent bleed of mixture BR-4 was less than that of mixture BR-1. The *W* and *W-Adj* factors of mixture BR-1 plotted off the Coarseness Factor Chart and consequently well above the trend bar as shown in Figure F1. This is indicative that the mixture was oversanded. The *W* and *W-Adj* factors of mixture BR-4 plotted approximately 6 percentage points above the Coarseness Factor Chart trend bar, indicating this mixture is also probably slightly oversanded, but not nearly so much so as mixture BR-1. The Shilstone mortar factors of both mixtures were high, but that of mixture BR-1 was approximately 3.5 percent greater than that of mixture BR-4, even though BR-4 had higher water and cementitious materials contents.

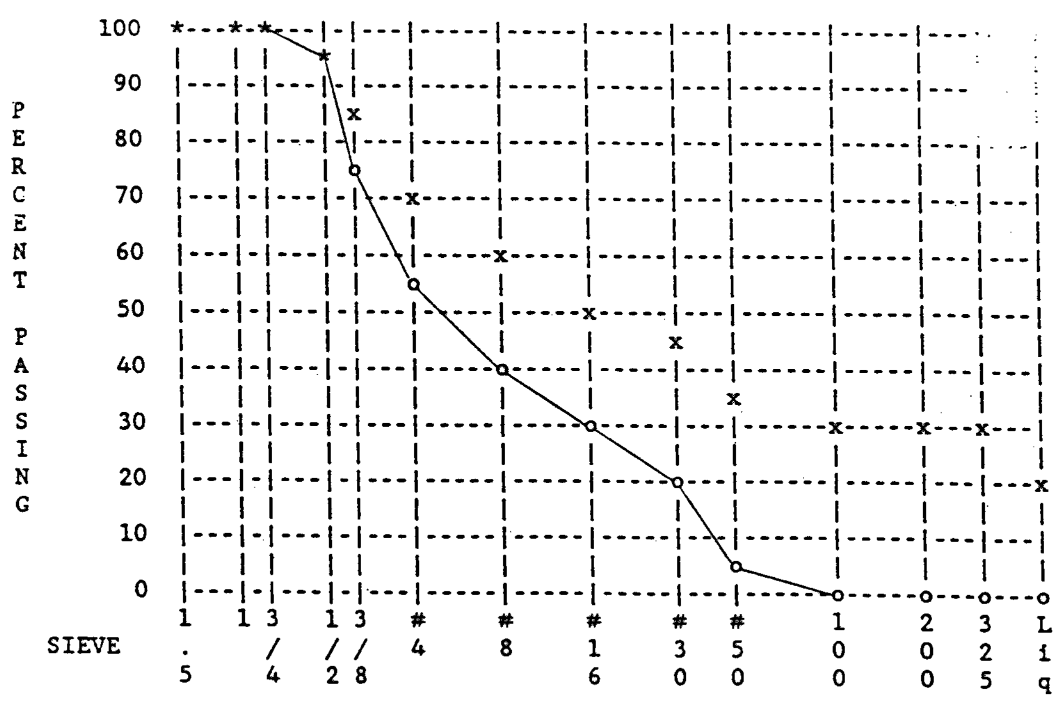
The two-point workability test results indicate that mixture BR-1 has a higher yield value than mixture BR-4; however, mixture BR-4 has a higher plastic viscosity. This seems to indicate that although mixture BR-1 may be more difficult to initially mobilize, once it is motion it requires slightly less energy to continue in motion than does mixture BR-4. Average two-point torque versus speed curves for the two mixtures are shown in Figure 17.

PSI: 4000 PSI Mix: WES 07/15/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND 1	SAND 2	PASTE	TOTAL	AGGR
1-1/2 "					100.0	100.0
1 "					100.0	100.0
3/4 "	100.0				100.0	100.0
1/2 "	89.0				96.4	94.8
3/8 "	47.0		100.0		82.9	75.1
# 4	4.0	100.0	99.0		68.9	54.7
# 8	2.0	89.0	24.0		59.4	40.9
# 16	-	70.0	2.0		51.6	29.6
# 30	-	44.0	-		44.0	18.5
# 50	-	16.0	-		35.9	6.7
# 100	-	3.0	-		32.1	1.3
# 200	-	-	-	100.0	31.3	-
# 325	-	-	-	94.6	29.6	-
Liquid	-	-	-	64.2	20.1	-

GRADATION CHART



x - ALL COMPONENTS o - AGGREGATES * - BOTH

Figure 16. Aggregate grading curve for Blue River Paved Reach Mixture BR-4

Table 18
Blue River Paved Reach Concrete Mixtures Proportions

Mixture	Saturated Surface-Dry Weights, kg/m^3 (lb/yd^3)					WRA[1]	HRWRA[1]	w/c
	Portland Cement	150 μm - 4.75 mm	600 μm - 9.5 mm	4.75 mm - 19.0 mm	Water			
BR-1	335 (564)	922 (1,554)	0	922 (1,554)	135 (227)	0.20 (3.0)	0.31 (4.8)	0.40
BR-2	335 (564)	597 (1,006)	469 (791)	728 (1,227)	151 (255)	0.20 (3.0)	0.52 (8.0)	0.45
BR-3	335 (564)	721 (1,215)	302 (509)	815 (1,373)	135 (227)	0.20 (3.0)	0.52 (8.0)	0.40
BR-4	352 (594)	758 (1,278)	199 (335)	850 (1,432)	141 (237)	0.33 (5.0)	0.26 (4.0)	0.41
BR-5	335 (564)	720 (1,214)	227 (382)	876 (1,476)	135 (227)	0.20 (3.0)	0.33 (5.0)	0.40

[1] Dosage rate is ℓ/100 kg (oz/100 lb) cement.

Table 19
Summary of Observations Blue River Paved Reach Trial Mixture Placements

Mixture	Placing and Vibration	Observation
BR-1	Easy to place, although appeared somewhat oversanded. Slightly sluggish under vibration; had tendency to segregate when placed at > 150 mm (6-in.) slump.	Floated easily, but surfaces seemed over-mortared due to high, fine aggregate content of the mixture.
BR-2	Mixture moved easily under vibration, but was harsh and rocky.	Finished poorly. Harsh texture made closing the surface very difficult. Difficult to broom without pulling coarse aggregate out of mixture. Finishers said mixture appearance was like "cottage cheese."
BR-3	Same as BR-2	Same as BR-2
BR-4	Mixture moved very easily under vibration. Held together, with minimal segregation	Finished much better than BR-2 & -3 but still somewhat rougher than BR-1. However, no problems in closing surface with float or in applying broomed finish.

Table 20
Summary of Blue River Paved Reach Fresh Concrete Test Results

Mixture	Slump mm (in.)	Unit Weight kg/m^3 (lb/ft^3)	Air Content percent	Bleed percent	Mortar Factor percent	W percent	W-Adj percent
BR-1	140 (5-1/2)	2,295 (143.3)	6.6	1.0	62.9	40.9	41.7
BR-4	150 (6)	2,302 (143.7)	6.3	0.3	59.4	47.0	47.0

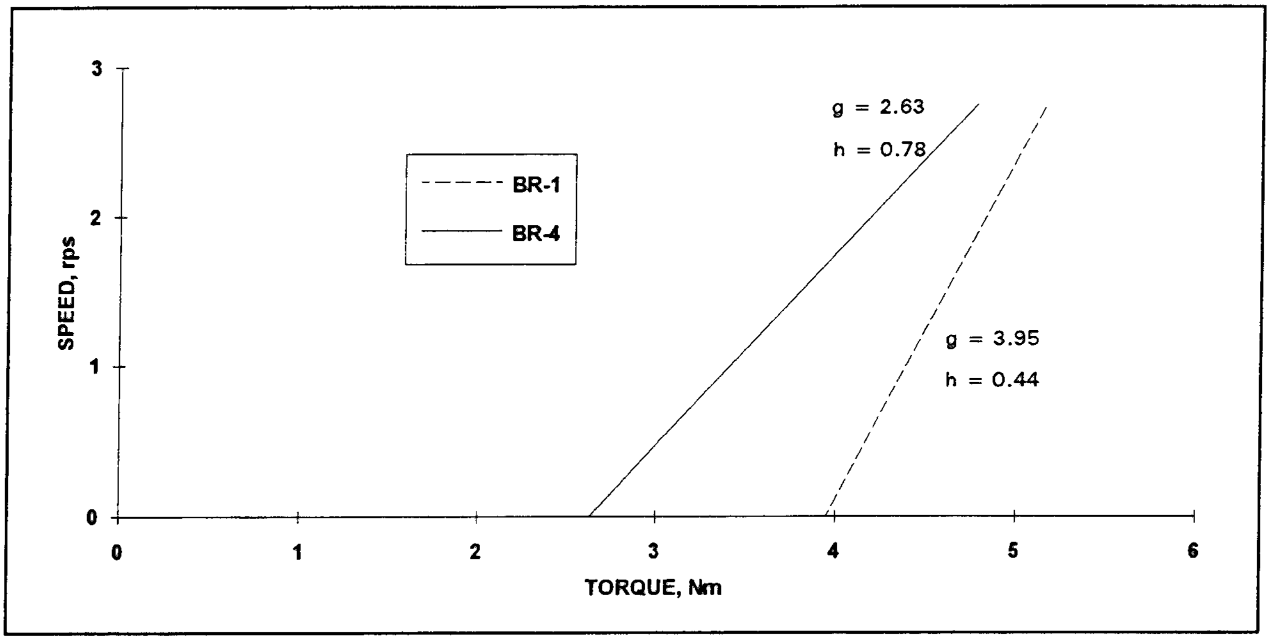


Figure 17. Average two-point workability results for Blue River Paved Reach mixtures BR-1 and BR-4

Individual hardened concrete test results are presented in Table F2. A summary of hardened concrete test results is given in Table 21. The average compressive strength test results indicate that neither the 7- nor 28-day strengths of the two mixtures are significantly different, even though the strengths of mixture BR-4 appear greater than those of mixture BR-1. The lack of statistical significance is due to the relatively large variance of the BR-1 strengths. The results of the resistance to underwater abrasion tests indicate that at the conclusion of the tests, mixture BR-4 had an average material volume loss less than mixture BR-1 had. This may be due to the improved combined aggregate grading of mixture BR-4 and to the fact that this mixture contained more of the harder siliceous aggregates. Both the resistance to chloride ion penetration and the length change of the two mixtures were approximately the same.

Table 21
Summary of Blue River Paved Reach Hardened Concrete Test Results

Mixture	Compressive Strength, MPa (psi)		Underwater Abrasion Loss, m^3	Chloride Ion Penetration coulombs	Length Change percent
	7-day	28-day			
BR-1	31.9 (4,630)	39.8 (5,770)	0.000710	3,290	0.027
BR-4	33.9 (4,920)	42.1 (6,110)	0.000571	3,290	0.025

Richmond Road

Background

During October and November 1991, the Texas Department of Transportation (TDOT), Texas Transportation Institute (TTI), Two States Construction Company, Shilstone Software Co., and WES cooperated in constructing and monitoring concrete pavement test sections on Richmond Road in Texarkana, TX. The test sections were opened to traffic in July 1992 and consisted of jointed concrete pavement placed 330 mm (13 in.) thick. Five different mixture proportions were used in the test sections. These mixtures were proportioned by Dr. Dan Zollinger, TTI, as part of an investigation to study the effects of aggregate proportions and characteristics on joint formation and behavior of the jointed concrete pavement. The test section paving direction was identical to the traffic direction. Different curing methods were used to control the drying of the concrete. Joints were cut with the conventional water-cooled blade after the concrete had sufficiently hardened but before cracking occurred and by use of a light, portable, concrete saw, which was used to dry-cut the concrete at very early ages. WES's participation in the project consisted of procuring aggregates to use in one of the mixtures so that relevant comparisons could be made between the properties of concrete mixtures proportioned in accordance with TDOT requirements and in accordance with concepts provided in seeMIX. Only two of the mixtures used in the test sections were, therefore, of interest to this CPAR project. Test section construction was performed by the Two States Construction Co., Texarkana, TX. Two States personnel also fabricated a number of the test specimens. Testing of all materials and test specimens was conducted by TTI staff members.

Materials and mixtures

ASTM C 150 (ASTM 1991g) Type I portland cement was used in the two mixtures of interest. In addition, fly ash, conforming to ASTM C 618 (ASTM 1991m), Class C, was also used as cementitious material in the concrete. One coarse aggregate and three fine aggregates were used in the mixtures. The coarse aggregate consisted of a 37.5-mm (1-1/2-in.) NMSA gravel which conformed to TDOT grading requirements. The fine aggregates consisted of natural and manufactured concrete fine aggregates and a very coarse natural fine aggregate termed "buckshot." The aggregate gradings are given in Table 22. A WRA was also used in the mixtures.

The mixtures used in this investigation were proportioned to achieve a slump of approximately 40 mm (1-1/2 in.) and an air content of approximately 5.0 percent. A flexural strength of 4.85 MPa (700 psi) at 28 days was also specified. Mixture RR-1 was considered the reference mixture and contained only the natural fine aggregate and the gravel coarse aggregate. The mixture contained 30 percent, by volume of cementitious material, Class C fly ash, and had a w/c of 0.39. The ratio of fine aggregate to total aggregate, by volume, in

Table 22
Richmond Road Aggregate Gradings

Sieve Size	Cumulative Percent Finer			
	Natural Fine Aggregate	Manufactured Fine Aggregate	Buckshot	Coarse Aggregate
37.5 mm (1-1/2 in.)				100
25.0 mm (1 in.)				85
19.0 mm (3/4 in.)				70
12.5 mm (1/2 in.)				40
9.5 mm (3/8 in.)	100	100	100	17
4.75 mm (No. 4)	99	100	86	2
2.36 mm (No. 8)	81	88	13	
1.18 mm (No. 16)	70	61	7	
600 μm (No. 30)	58	39	6	
300 μm (No. 50)	17	23	2	
150 μm (No. 100)	1	10	0	
75 μm (No. 200)	0	3		

the mixture was 37 percent. The grading curve shown in Figure 18 illustrates the typical "stair-stepped" grading obtained when one coarse and one fine aggregate are combined. Approximately 61 m (200 ft) of pavement test section were constructed using mixture RR-1. Mixture RR-2 contained the intermediate aggregates recommended by Shilstone which caused the combined grading of the mixture to closely match the 0.45 power grading curve. The combined grading curve is shown in Figure 19. Approximately 46 m (150 ft) of test section were constructed using mixture RR-2. The proportions of mixtures RR-1 and -2 are given in Table 23.

Fresh and hardened test results

Testing conducted during this investigation focused on hardened concrete tests. Both mixtures were produced within the specified slump and air contents. Mixture RR-1 had a Shilstone mortar factor of 49.3 percent, which is within the limits recommended by Shilstone (1990) for paving mixtures. The *W* and *W-Adj* factors plotted approximately 0 to 2 percentage points above the Coarseness Factor Chart trend bar as shown in Figure 20. Mixture RR-2 had a Shilstone mortar factor of 50.7 percent, which is only slightly above the 50-percent maximum recommended by Shilstone for paving mixtures. Again, the *W* and *W-Adj* factors plotted approximately 0 to 2 percentage points above the

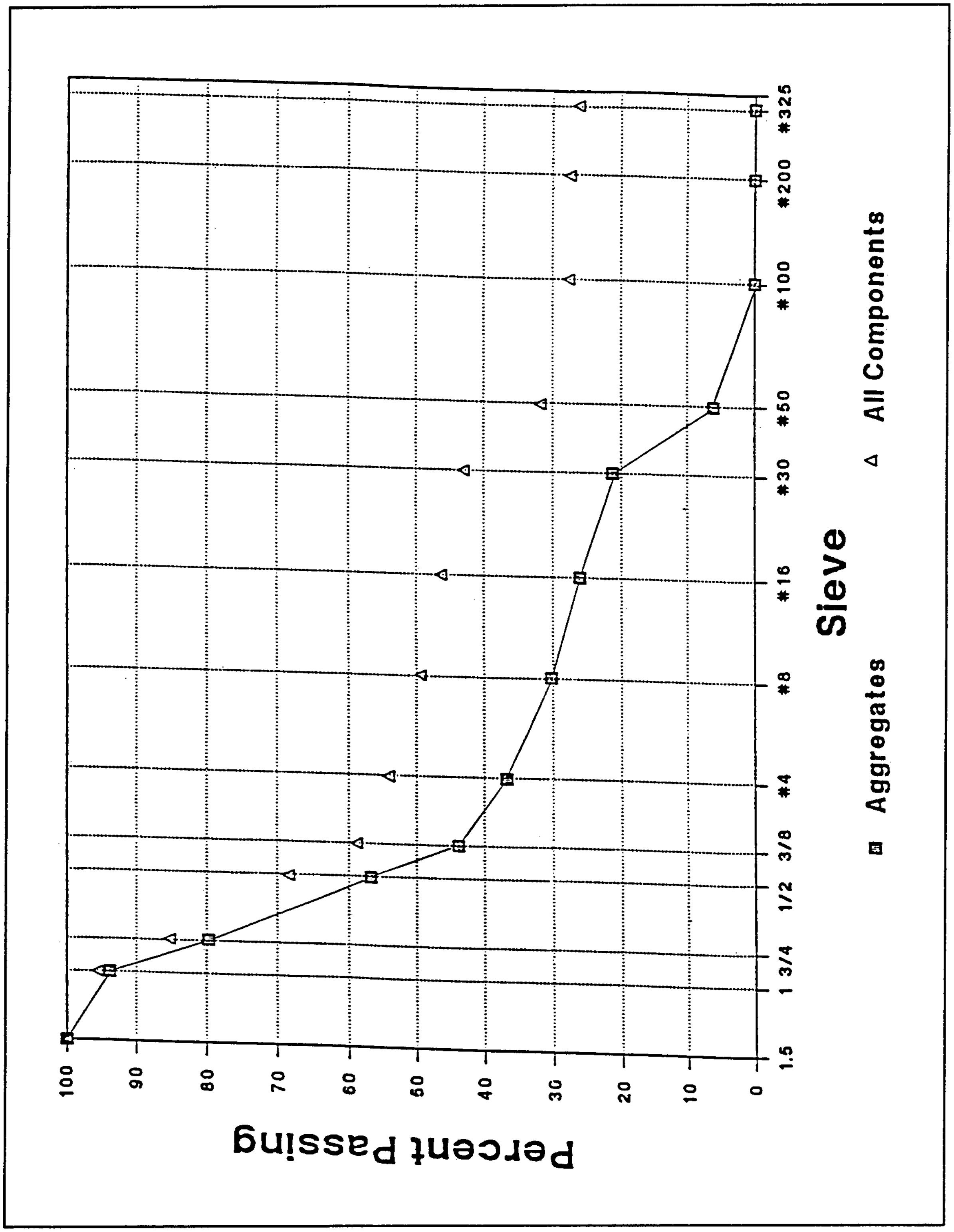


Figure 18. Aggregate grading curve for Richmond Road mixture RR-1

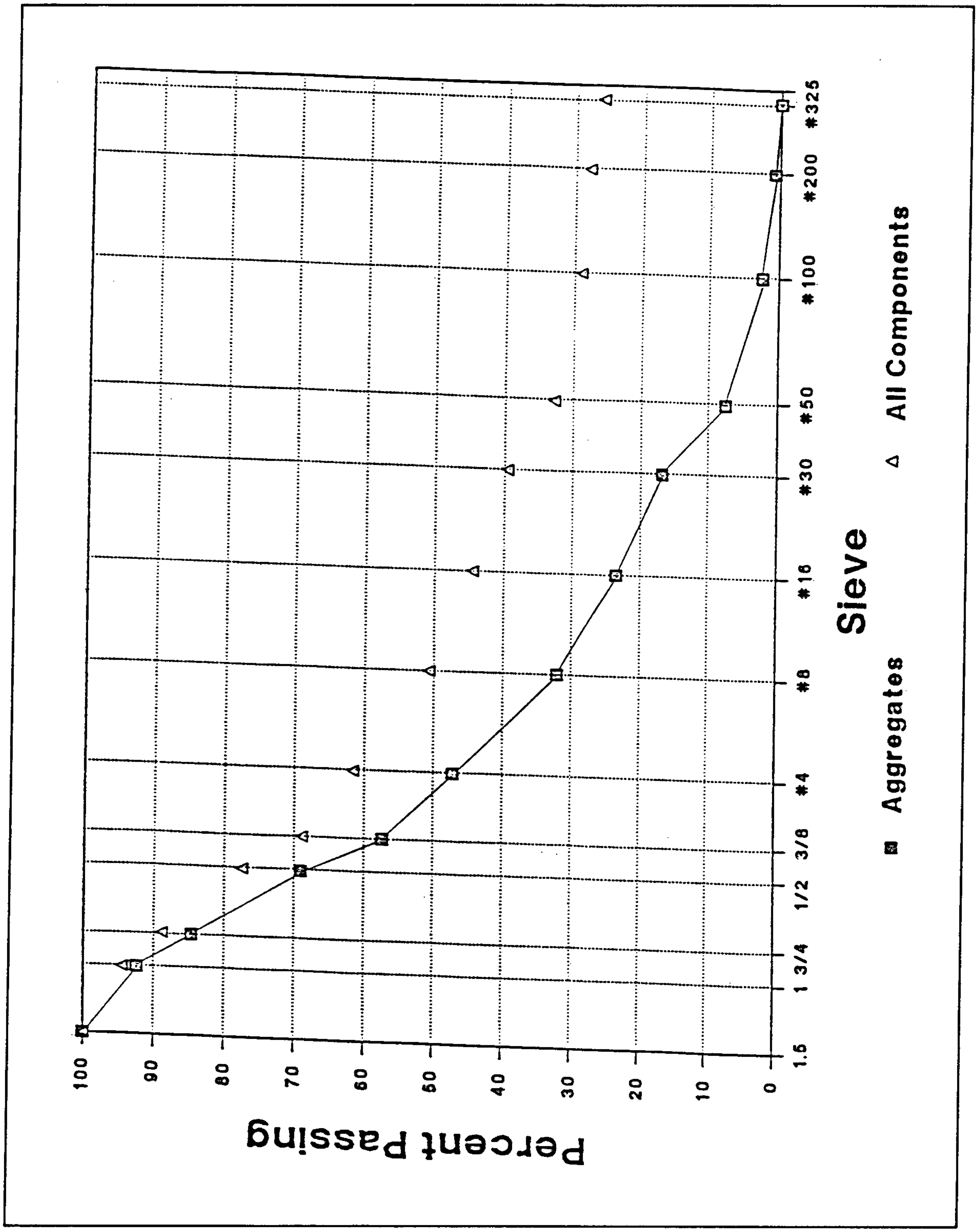


Figure 19. Aggregate grading curve for Richmond Road mixture RR-2

Table 23
Richmond Road Concrete Mixtures Proportions[1]

Mixture	Saturated Surface-Dry Weights, kg/^{3} (lb/yd^3)							WRA	w/c
	Portland Cement	Fly Ash	Natural Fine Aggregate	Manufactured Fine Aggregate	Buckshot	Gravel Coarse Aggregate	Water		
RR-1	225 (379)	84 (142)	704 (1,187)	0	0	1,175 (1,980)	122 (205)	0.33 (5.0)	0.39
RR-2	225 (379)	84 (142)	237 (400)	436 (735)	242 (408)	960 (1,618)	122 (205)	0.35 (5.0)	0.39

[1] Dosage rate is ℓ/100 by cement.

Coarseness Factor Chart trend bar, as shown in Figure 21. No noticeable differences between the two mixtures were observed as they were placed, or in the condition of the test section surfaces. However, records from Zollinger indicate cores taken from the test section constructed with mixture RR-1 contained more large voids than those taken from the test section constructed with mixture RR-2. Cores representing mixture RR-1 had voids whose largest dimension approached 25 mm (1 in.) and whose spacing was approximately 25 to 50 mm (1 to 2 in.). Cores representing mixture RR-2 also contained numerous voids having spacing as small as 6 mm (1/4 in.); however, the voids were much smaller in size. In both cases more vibration was apparently needed. However, the larger voids in the cores representing mixture RR-1 may have also been the result of an absence of intermediate particles.

The quality of the concrete placed in the test sections was controlled on the basis of compressive strength rather than flexural strength. Earlier work by TTI indicated that a compressive strength of approximately 31.7 MPa (4,600 psi) was needed to assure a flexural strength of 4.85 MPa (700 psi) at 28 days. Flexural strength tests conducted at 7 days during the development of mixture proportions resulted in an average strength of 4.55 MPa (660 psi) for mixture RR-1 and 4.80 MPa (695 psi) for mixture RR-2. Average 28-day compressive strength of mixture RR-1 was 37.3 MPa (5,410 psi) and 36.9 MPa (5,360 psi) for mixture RR-2.

One hundred-millimetre (4-in.) diameter cores were taken from the test sections and measured for compressive and splitting tensile strength and modulus of elasticity. Since only one core was tested for each property, only marginal significance should be placed on the results. The compressive strengths of cores representing mixtures RR-1 and 2 were 41.6 and 44.8 MPa (6,030 and 6,490 psi), respectively. The splitting tensile tests were conducted on 76-mm (3-in.)-long sections of the cores to assess how strength varied with pavement depth. The top of the test section containing mixture RR-1 had a splitting tensile strength of 4.10 MPa (595 psi), while the bottom had a strength of 5.00 MPa (725 psi). The top of the test section containing mixture RR-2 had a splitting tensile strength of 5.40 MPa (780 psi), while the bottom had a strength of 5.80 MPa (840 psi). Consequently, it appears that the strength of both test sections increased with depth and that mixture RR-2 was stronger than mixture RR-1, regardless of

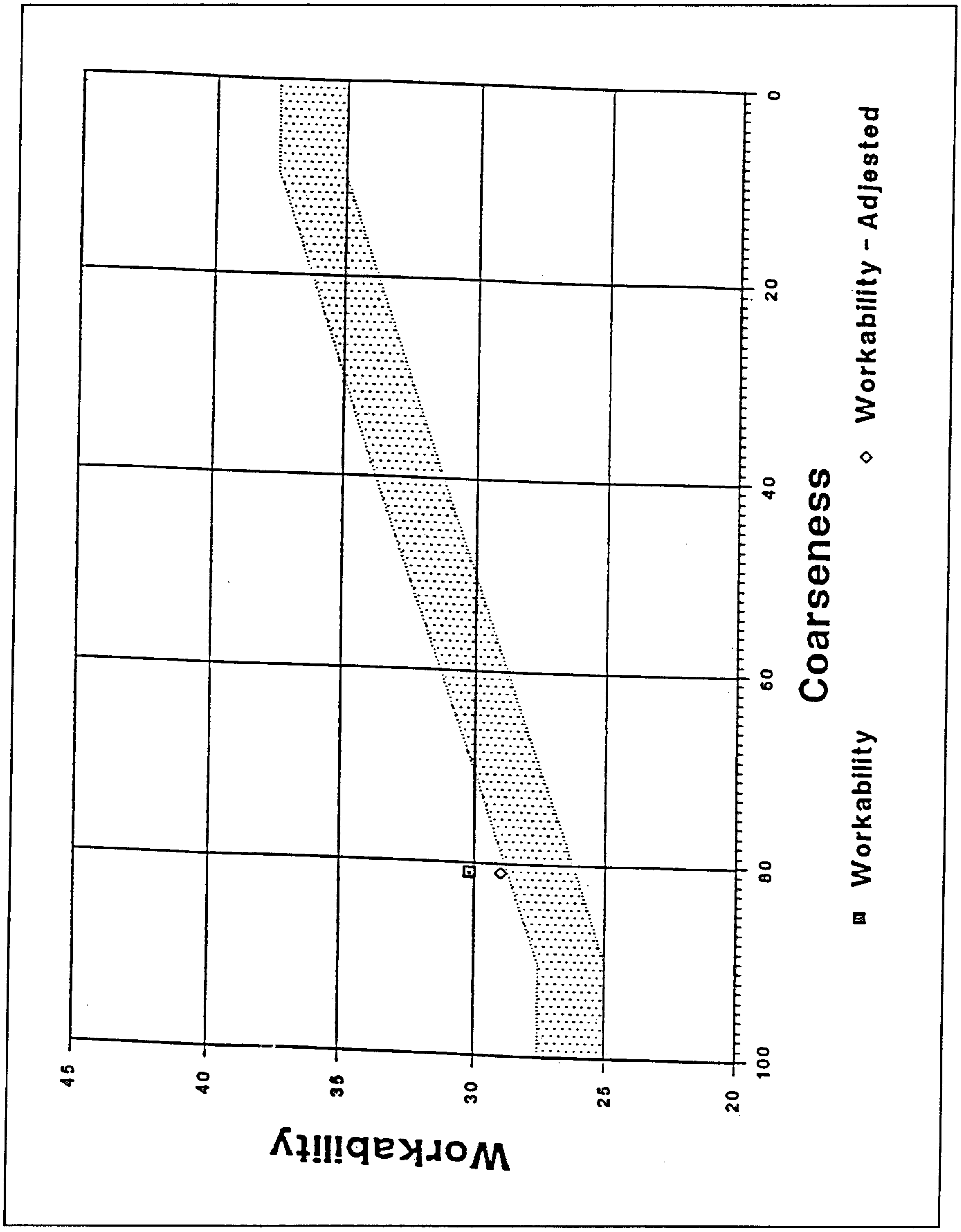


Figure 20. Coarseness Factor Chart for Richmond Road mixture RR-1

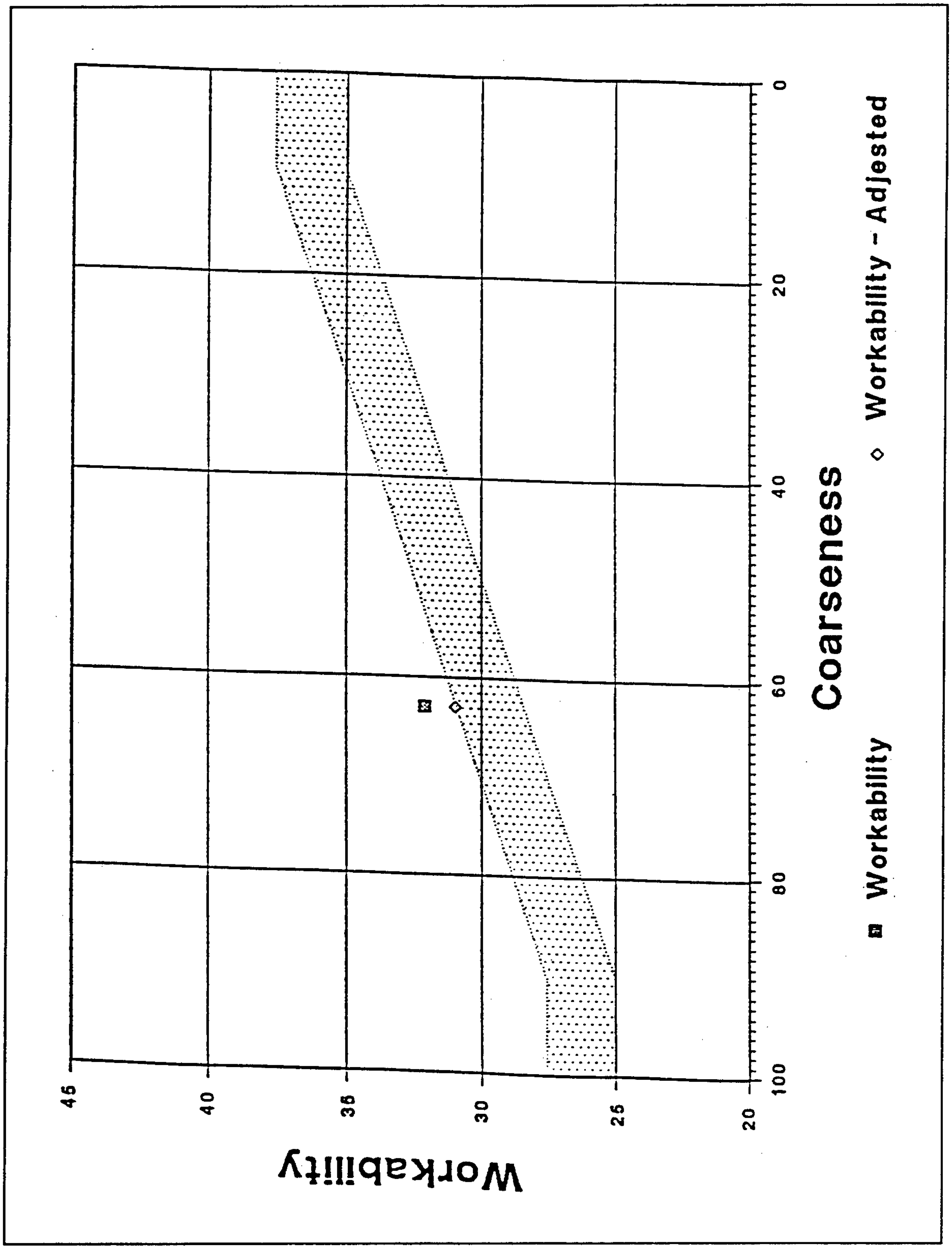


Figure 21. Coarseness Factor Chart for Richmond Road mixture RR-2

depth. The higher splitting tensile strength may have been the result of greater aggregate interlock in mixture RR-2, which contained the intermediate aggregate sizes. Notes from Zollinger indicate that the improved total aggregate grading of mixture RR-2 also appeared to improve the probability that cracking would occur through sawed joints. When the test sections were opened to traffic, 100 percent of the saw-cut joints in the test section constructed with mixture RR-2 were cracked, while only 75 percent of the joints in the RR-1 test section were cracked.

6 Evaluation of SeeMAT

System Requirements

SeeMAT consists of three menu-driven software programs whose primary objective is to provide database management of aggregate, cement, and pozzolan data and to provide statistical and graphical tools for analysis and presentation of those data. The three seeMAT programs include seeMAT-A for use with concrete aggregates, seeMAT-C for cement, and seeMAT-P for pozzolans. The programs require an IBM-compatible computer (although some non-IBM formats can be made to work) with a 386 or higher processor and 640 kbytes of RAM. At least 530 kbytes of that RAM must be free for program use after booting. The seeMAT-C program requires 1.2 megabytes (Mb) of hard disk space. The seeMAT-P and seeMAT-A programs each require 1.0 Mb of hard disk space. Additional space is required for data storage. Shilstone Software Co. recommends at least 20 Mb per program. MS DOS version 2.1 or PC DOS 2.1 or greater is required. CGA, EGA, or VGA graphics are supported. Printers must be parallel and able to emulate an Epson graphics format. This includes most dot matrix, ink jet, and laser printers.

Description of SeeMAT Program

Each program is divided into two parts: data entry and data analysis. Data entry is further divided into subroutines that accept entry of specification values, generic material descriptions, and test data. Data analysis is further divided into subroutines that allow for the generation of tabular reports, performance analysis, frequency distributions, regression analysis, time-line charts, and strength-gain curves. These are described in more detail in the following sections. In addition, seeMAT-A enables the user to blend up to 10 different aggregates according to cost, specification requirements, or other criteria. This feature is extremely useful in developing potential combined-aggregate gradings for use in seeMIX. It also has been useful for maintaining the coarse aggregate blends prescribed in the mass concrete mixture proportions used on some Corps of Engineers civil works projects.

SeeMAT data entry

Specifications. SeeMAT is an important component of the SmartPlant program because it provides the means for materials data management and enables the user to quickly ascertain compliance with material specification requirements. SeeMAT-A, -C, and -P each contain predefined specifications. The specifications included in seeMAT-A include several of those found in ASTM C 33 (ASTM 1991a) along with some from Federal Government agencies and state departments of transportation. SeeMAT-C and -P include specifications for portland cement, blended cement, and fly ash requirements described in ASTM C 150 (ASTM 1991g), ASTM C 595 (ASTM 1991*l*), and ASTM C 618 (ASTM 1991m), respectively. Custom specifications may be created by the user by changing the numerical values of the requirements in one of seeMAT-C or -P existing specifications. SeeMAT-A permits the user to build a specification without using one of the predefined specifications. Twelve sieve sizes are preassigned to seeMAT-A as defaults; however, the user has the flexibility to add or delete sieve sizes to match a specification of interest. Aggregate specific gravity may be entered into seeMAT-A as bulk, bulk (saturated surface-dry), or apparent. Grading specifications may be recorded as cumulative percent passing each sieve, cumulative percent retained on each sieve, or individual percent retained on each sieve. Nonstandard test requirements can be included in a seeMAT specification through the use of user-defined fields or through an "Other Data" screen.

Material description. This subroutine allows the user to define a classification system for test data. This allows samples from a single project, source, or other common feature to be grouped together for analysis. Any number of descriptions may be created by the user. For example, aggregates may be tied to a specification identification; classified according to type, shape, geologic description, and nominal maximum size; and have cost and supplier information annotated. Additional information, such as project identification, testing laboratory, etc., may be entered as user codes.

Test data. Data input fields are automatically generated based on the specification description in use. The fields include the name of the test and units in which data are to be entered. SeeMAT has a feature that will convert data to other units of measure. The seeMAT-C program allows Bogue compounds to be either entered manually or calculated from entered oxide data. However, the program does not automatically include the values of TiO_2 and P_2O_5 in the calculation of C_3A, as directed by ASTM C 150 (ASTM 1991g). Also, the program does automatically adjust the Bogue calculations for the condition when Al_2O_3-Fe_2O_3 ratio is less than 0.64, as directed by ASTM C 150.

The user may lose some flexibility generating custom reports when C_3A is near to zero, but this is not a serious problem. While seeMAT-A enables the user to make sieve analysis calculations and construct grading worksheets, it will not save the aggregate masses retained on each sieve entered into the program by the user.

The user enters the sample numbers and sample dates. Any combination of numbers and characters can be used for a sample-numbering system. The program sorts samples alphanumerically.

The program includes the conversion feature that allows data to be entered in the commonly used non-SI units found in the ASTM specifications and converts them to SI units.

SeeMAT data analysis

The data-analysis feature of the seeMAT allows for seven types of data analyses: tabular reports, frequency-distribution charts, cusum charts, time-line charts, regression analysis, strength-gain curves, and aggregate blending. A utility feature also exists for importing or exporting data from or to ASCII files. Several predefined reports are included for each of the seven types for properties that are commonly of concern, such as chemical properties and strength, but custom reports can also be designed by the user. The seven data-analysis procedures are described below with examples of output.

Tabular. This reporting feature allows either batch reports, containing multiple material identifications and properties, or performance-analysis reports. The batch reports include capability to calculate descriptive statistics, such a mean, standard deviation, range, and coefficient of variation. Quite a bit of flexibility is allowed in generating batch reports. Performance-analysis reports compare test results with specification requirements and mark those samples that fail to meet requirements. An example of a seeMAT-A performance report for aggregate grading is illustrated in Figure 22.

Frequency distribution

Frequency-distribution charts are useful as visual aides in analysis of sample-to-sample variation in a property. Many people find them more useful than descriptive statistics for visualizing the amount of variation that exists in a particular property and for determining whether the variation is uniform about the mean value or whether some skewness exists in the data. An example is illustrated in Figure 23.

Cusum charts

Cusum charts provide a sensitive way of determining whether a material property is drifting away from a target value. It is similar to a time-line chart, but the calculation of the cusum statistic results in a more sensitive detection of small but consistent changes in a property. An example is illustrated in Figure 24.

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Performance Analysis 05/05/92 1

AGGREGATE DESCRIPTION
====================

aggmedium ---------- 6/25/91

Class : Coarse Shape : Cubical
Type : Crushed Geology : Limestone

Maximum aggregate size : # 67 -- 3/4

SPECIFICATION
=============

specmedium ---------- 6/24/91

1 1/2" stone

	Ind % Pass 2 "	Ind % Pass 1-1/2 "	Ind % Pass 1 "	Ind % Pass 3/4 "	Ind % Pass 3/8 "
Low	100.0	90.0	20.0	0.0	0.0
High	100.0	100.0	45.0	10.0	5.0

Sample ID	Sample Date	Seq Num	Ind % Pass 2 "	Ind % Pass 1-1/2 "	Ind % Pass 1 "	Ind % Pass 3/4 "	Ind % Pass 3/8 "
44	1/29/92	1	96.0 <	69.0 <	29.0	4.0	1.0
45	2/ 4/92	2	100.0	95.0	34.0	5.0	1.0
46	2/12/92	3	100.0	92.0	37.0	3.0	1.0
47	2/19/92	4	100.0	97.0	50.0 >	6.0	2.0
48	2/27/92	5	100.0	94.0	41.0	6.0	2.0
49	3/ 5/92	6	100.0	95.0	33.0	5.0	1.0
50	3/10/92	7	100.0	92.0	47.0 >	8.0	1.0
51	3/16/92	8	100.0	92.0	34.0	2.0	1.0
52	3/24/92	9	100.0	92.0	43.0	6.0	1.0
53	3/31/92	10	100.0	93.0	40.0	3.0	1.0
54	4/ 7/92	11	100.0	96.0	46.0 >	6.0	1.0
55	4/14/92	12	100.0	96.0	51.0 >	8.0	1.0
56	4/21/92	13	100.0	93.0	33.0	6.0	1.0
57	4/27/92	14	100.0	99.0	46.0 >	9.0	2.0
Count			14	14	14	14	14
Average			99.7 <	92.6	40.6	5.5	1.2
Standard Deviation			1.1	7.1	6.8	2.0	0.4
Range			96.0	69.0	29.0	2.0	1.0
			100.0	99.0	51.0	9.0	2.0

Figure 22. Example aggregate performance report. ">" and "<" symbols indicate samples that are greater than or less than specification requirements, respectively

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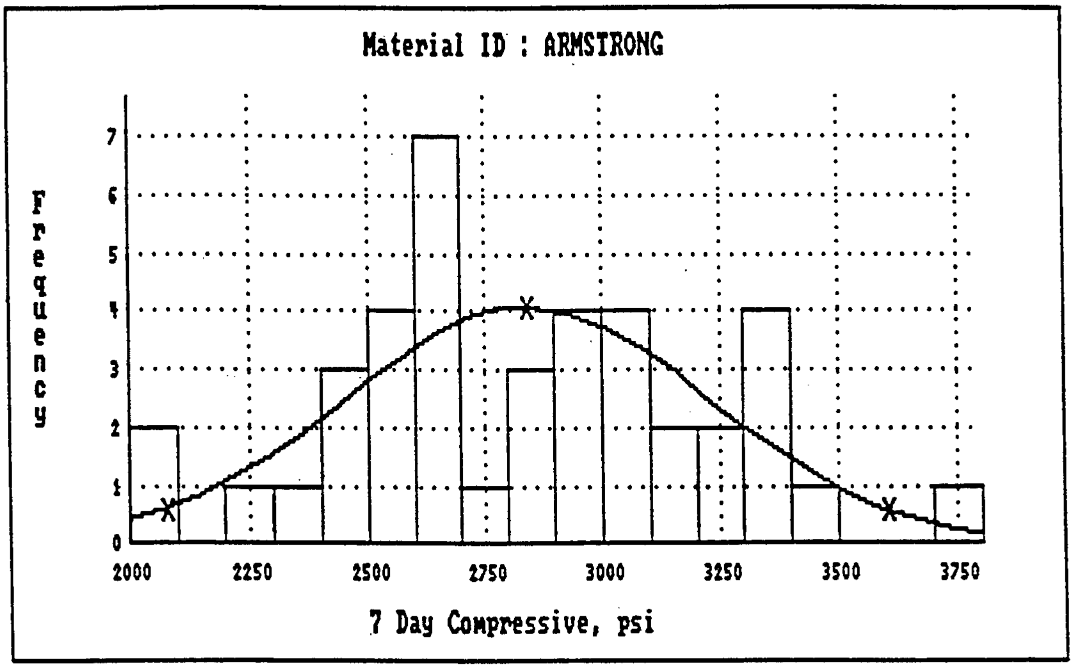
Frequency Distribution of ARMSTRONG



SUMMARY STATISTICS

Number of tests	-	40
Minimum	-	2080
Maximum	-	3750
Average	-	2840
Standard deviation	-	389
Median	-	2835
Interval	-	100

FREQUENCY DISTRIBUTION

------ Range ------ Lower	Upper	Count	Percent	Cumul Percent
2000	2100	2	5.00	5.00
2100	2200	0	0.00	5.00
2200	2300	1	2.50	7.50
2300	2400	1	2.50	10.00
2400	2500	3	7.50	17.50

Figure 23. Example frequency-distribution report for 7-day compressive strength. To convert pounds per square inch to megapascals, multiply by 0.006894757

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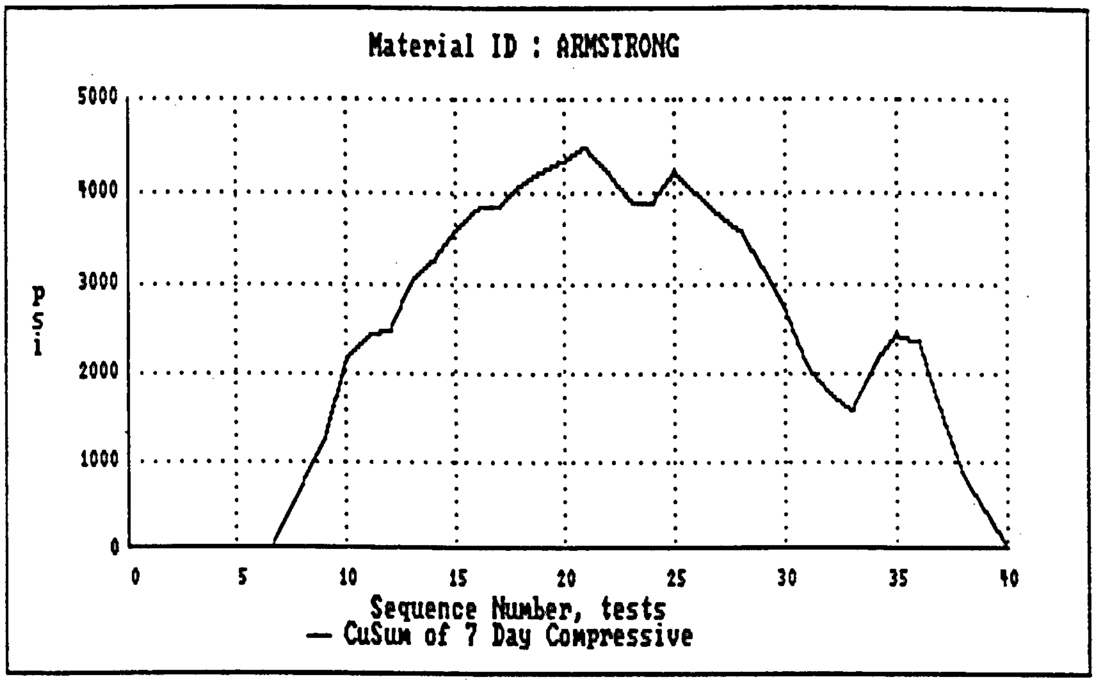
CuSum Analysis of ARMSTRONG



SUMMARY STATISTICS

Target average	-	2840
Number of tests	-	40
Actual average	-	2840
Standard deviation	-	389
80% confidence interval :		
Low	-	2343
High	-	3339
98% confidence interval :		
Low	-	1935
High	-	3748
Minimum	-	2080
Maximum	-	3750

Figure 24. Example of Cusum analysis of 7-day compressive strength. To convert pounds per square inch to megapascals, multiply by 0.006894757

Time-line charts

Time-line charts are simple plots of test results versus time or sample number. These are simple but very useful in detecting trends in the properties of a material. Critical and/or control limits can be superimposed on these plots through use of the "reference values" input fields. This program also allows moving averages to be calculated and plotted. Figure 25 illustrates a time-line analysis output for one aggregate sieve size. Similar output could be generated for other aggregate properties, cementitious material strength, etc.

Regression analysis

Both simple and multiple, linear, regression analyses can be performed. These tools allow the user to determine whether there is a significant relationship between changes in one variable (dependent variable, Y) and changes in one or more other variables (independent variables, X). Up to 12 independent variables can be selected. For example, one could use this tool to determine whether observed changes in C_3S levels in cement are related to observed changes in compressive strength and fineness. This tool works best if the relationships are linear, but slight nonlinearities are not a serious problem.

For simple X-Y data, some nonlinearities can be handled with the binomial regression feature. This feature fits a second-order polynomial to these data. More complicated functional relationships may not be detected by this technique. SeeMAT also includes a plotting feature that shows the data and fitted curve. Figure 26 illustrates the output from this procedure.

Strength-gain curves

This feature in the seeMAT-C program is dedicated primarily to use of strength data collected at standard test ages to be used to predict strength at other hypothetical test ages. The program plots individual specimen strengths against either age or log age, chosen by the user, and then calculates a linear regression curve. An interactive window is then presented that allows the user to input any test age, and predicted compressive strengths will be calculated. Eighty and ninety-eight percent confidence intervals are also calculated to give the user some idea about the reliability of the prediction. Figure 27 illustrates the graphical output and interactive window used in this program.

Aggregate blending

SeeMAT-A is capable of blending up to 12 aggregates with as many as 12 sieves for either the closest fit to the median of a particular grading specification, lowest total aggregate cost, or manual entry by the user for a customized aggregate blend. The user initiates the aggregate blending feature by either selecting a predefined blending specification or creating a new one, entering

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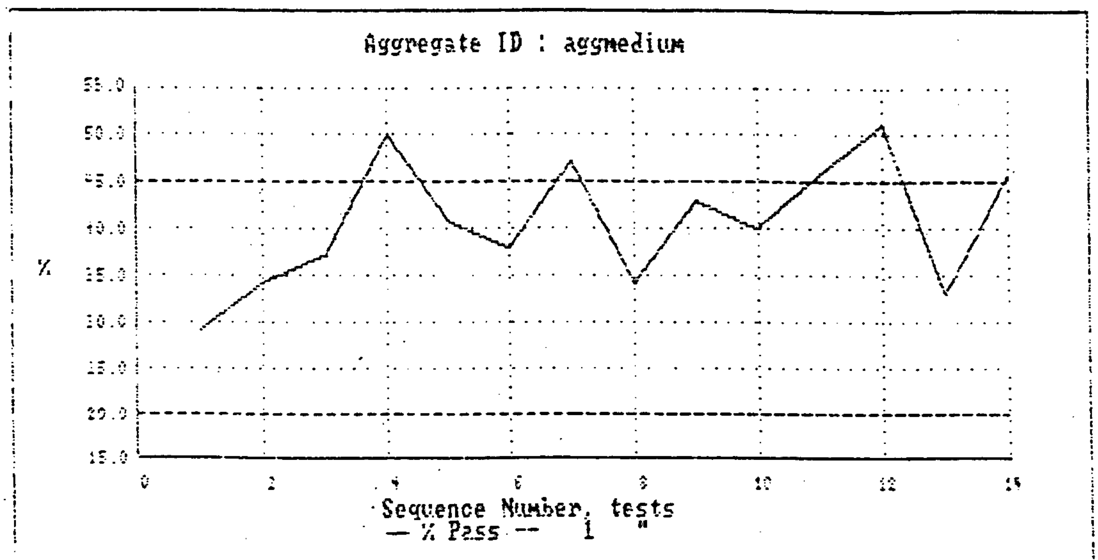
Time-Line Analysis

05/05/92



SUMMARY STATISTICS

---------- Variable ----------	Average	Std Dev	Low	-- High	Recs
% Pass -- 1 "	40.5	6.8	29.0	51.0	14

Units : %
Total number of selected records : 14

Figure 25. Example of time-line analysis for one aggregate sieve size

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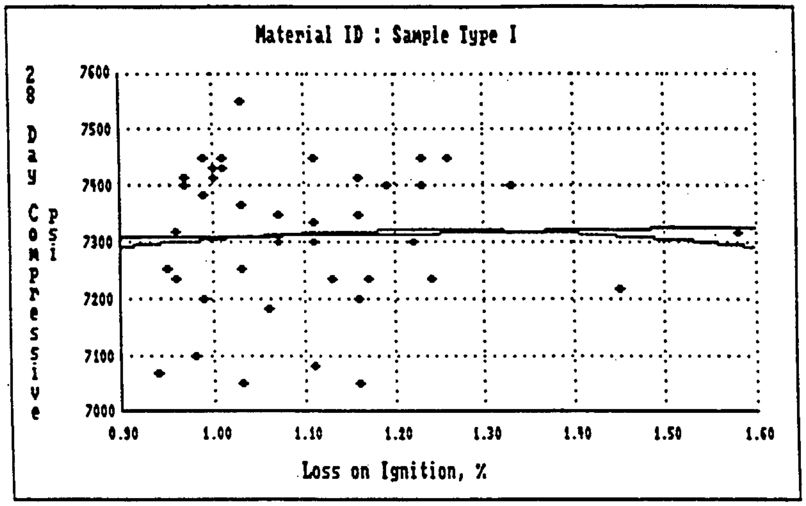
Regression Analysis of Sample Type I



REGRESSION ANALYSIS

Number of tests = 40
y = 28 Day Compressive x = Loss on Ignition

LINEAR RESULTS [y = A + Bx]

A = 7280
B = 30.10
Standard error of estimate = 129.0
Coefficient of correlation = 0.03290
Coefficient of determination = 0.001080

POLYNOMIAL RESULTS [y = A + Bx + Cx^2]

A = 6930
B = 626.0
C = -249.0

Standard error of estimate = 129.0
Index of correlation = 0.06520

(REGRESSION ANALYSIS -- Continued)

Index of determination = 0.004250

SUMMARY STATISTICS

------- Variable -------	Average	Std Dev	Low	-- High
28 Day Compressive	7310	128	7050	7550
Loss on Ignition	1.10	0.14	0.94	1.58

Figure 26. Example of regression analysis capabilities. To convert pounds per square inch to megapascals, multiply by 0.006894757

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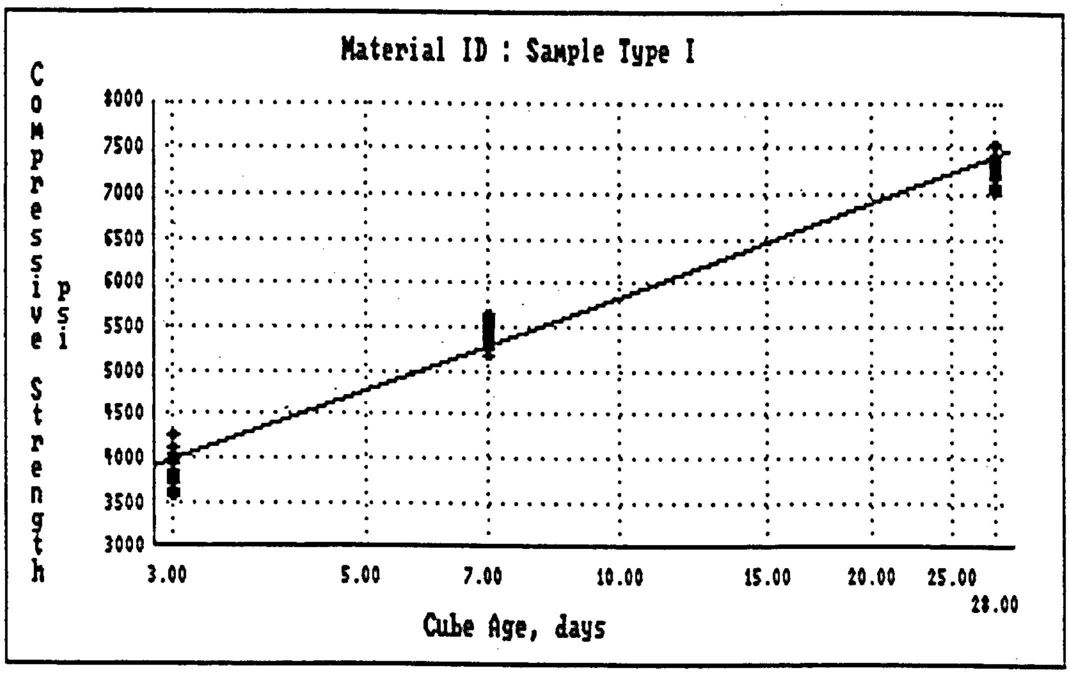
Strength Gain of Sample Type I



STRENGTH GAIN ANALYSIS

Number of tests - 120
y - Compressive Strength   x - Cube Age

REGRESSION RESULTS [y - A + (B * log x)]

A - 2310
B - 3510
Standard error of estimate - 193.0
Coefficient of correlation - 0.9910
Coefficient of determination - 0.9820

Figure 27. Example of cement strength-gain report. To convert pounds per square inch to megapascals, multiply by 0.00684757

sieve analysis data for each aggregate group to be included in the blend, and selecting the desired type of blend desired. The program then creates a tabular blending report and up to four different graphs of the aggregate blend. These include cumulative percent passing, cumulative percent retained, individual percent retained, and the 0.45 power grading curve. This feature is very useful in creating blends for use with the seeMIX program and also as a quality assurance tool. For example, EM 1110-2-2000 (Headquarters, Department of the Army 1994b) states that for Government mixture proportions, "as gradings of individual coarse aggregate size groups change, the proportions of the size groups should be adjusted so that the combined coarse aggregate grading approximates the maximum density grading." This could be easily done using seeMAT-A by entering the maximum density grading referred to a blend specification, periodically retrieving the sieve analysis test results for the aggregate groups of interest, and performing the blend to the median of the maximum density specification. If the gradings of one or more of the coarse aggregate size groups had changed significantly, the revised blend would enable the user to recommend appropriate adjustments in the mixture's aggregate proportions. Figure 28 illustrates a cumulative percent passing aggregate blend of three aggregates.

Data import/export

Data are exchanged with other software by this feature. SeeMAT programs read data from ASCII delimited files; therefore, data entered in another program, such as a spreadsheet, must be exported to such a file before it can be read by seeMAT. SeeMat exports data into ASCII files either with or without delimiters. Both import and export features provide a window that allows the user to select data to be exported from a file or to describe the fields into which data are to be imported.

Review of SeeMAT-C and -P

The Cement and Pozzolan Unit (C&PU), Concrete and Materials Division (CMD), Structures Laboratory, WES, conducted an abbreviated review of these programs. This group tests a wide variety of cements, pozzolans, and other related materials for specification compliance during construction of various Government construction projects. Therefore, data-management requirements are somewhat different from the requirements of a single project or a cement or pozzolan production facility, for which the seeMAT program is designed. The C&PU prefers to keep all test data in a single data file that is accessible by one of a number of properties of the material represented, such as name of manufacturer, location of manufacturer, project, specification requirements, sponsor, etc. In contrast, a construction project normally needs to maintain data on a single source of material. These different data-management requirements affect somewhat the suitability of a particular data-management program.

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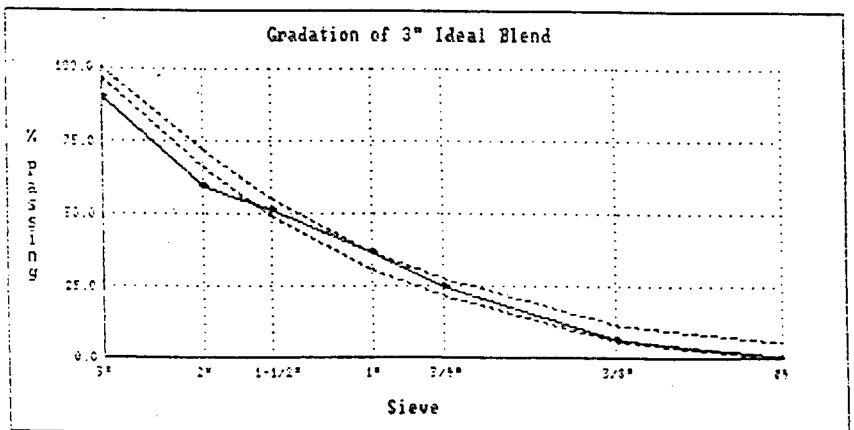
Aggregate Blend 05/11/92

AGGREGATE BLEND -- MANUAL

Specification ID : 3" Ideal Blend Blend ID : 3" Ideal Blend

Sieve	Low	High	% Pass	Aggregate	Pct
3 "	97.0	100.0	90.3 <	agglarge	* 50.0
2 "	66.0	72.0	59.6 <	aggmedium	* 25.0
1-1/2 "	49.0	55.0	51.4	aggsmall	* 25.0
1 "	31.0	37.0	36.7		
3/4 "	22.0	28.0	25.2		
3/8 "	6.0	12.0	7.2		
# 4	-	6.0	0.6		

Cost - Fineness modulus 8.25



AGGREGATE GRADATIONS -- % PASS

Sieve	agglarge Avg of 5	aggmedium Avg of 5	aggsmall Avg of 5
3 "	80.6	100.0	100.0
2 "	19.2	100.0	100.0
1-1/2 "	5.0	95.4	100.0
1 "	1.8	43.2	100.0
3/4 "	-	6.4	94.4
3/8 "	-	1.2	27.4
# 4	-	-	3.0
Cost	-	-	-

Figure 28. Example of aggregate blending report

The principal strength of the seeMAT programs is that they provide predefined user fields for cement and pozzolan data storage and analysis combined with predefined plotting and printing features. This obviates the need to adapt database, statistical, graphic, and/or spreadsheet software to this specific purpose by combining some of the features of each into a single program. Users who are versatile in this software may prefer the greater flexibility allowed by custom development of such programs, but novices can use the seeMAT programs largely without any understanding or prior experience with any of these programs.

Since the program sorts sample numbers alphanumerically, the user needs to give some attention to sample-number design. For example, if the calendar year is part of the sample number and it is desired that samples be sorted first by year, then the first digits of the sample number must be the calendar year.

Some users will find the separation of cement and pozzolan data into two separate programs an inconvenience. For example, a multipurpose testing laboratory may prefer to keep data from tests of many different materials in a single database. The seeMAT programs allow for only cements and pozzolans and require that one program be exited before use of the other is initiated. When only cement and pozzolan data are being monitored, this limitation would not be serious.

Three design features may cause problems, two of which are in the seeMAT-P program. First, the 325 sieve field is listed as "percent passing." The common way to express this result is "percent retained." Second, there is a field for "R-value." This is a specification that is not recognized by ASTM or the Corps of Engineers. R-value is probably the same as "R-factor." R-factor is used by the U.S. Bureau of Reclamation as an indicator of relative sulfate resistance expected to be contributed by fly ash. It is calculated according to the following equation.

$$R = \frac{CaO - 5}{Fe_2O_3} \tag{8}$$

where

Ca = calcium

Fe = iron

High values are associated with poor resistance to sulfate. The Corps of Engineers does not specify R-factor.

The third problem is in the seeMAT-C program. As mentioned, the subroutine of the program that calculates the Bogue compounds uses values for Al_2O_3 and Fe_2O_3 to calculate C_3A. ASTM C 150 (ASTM 1991g) requires that P_2O_3 and TiO_2 also be included in this calculation. To accomplish this correctly with this program, the sum of Al_2O_3, P_2O_3, and TiO_2 must be entered into the Al_2O_3 field. This results in a correct Bogue calculation, but incorrect Al_2O_3 data.

One of the unique features of this software is that is incorporates more sophisticated statistical calculations than is common with most database management or spreadsheet software. Because of the simplicity with which these calculations can be made, there is considerable opportunity for abuse of these procedures by individuals who do not understand the assumptions and limitations of the methods. This is not specifically a criticism of the software, but more a caution that the output from the statistical analysis part of the program could, if used indiscriminately, communicate information that has no basis in reality.

Review of SeeMAT-A

No formal review of this program was performed at WES. Rather WES arranged for Shilstone Software Co., as part of this CPAR project, to send copies of the program to the Gray's Landing and Point Marion Resident Offices located within the USAED, Pittsburgh. Both resident offices used the program during mass concrete production. Based upon comments from Corps of Engineers personnel who used the program at these projects, the following constructive critical remarks are made:

a. Provisions should be made to permit deletion of certain data files. For example, if sample dates are incorrectly entered, they cannot be easily deleted.

b. Additional data columns should be provided in the tabular reports.

c. Provisions should be made for comments and remarks.

d. An option should be provided which enables the user to manually flag data outside the specification range without running a performance analysis.

e. Provisions should be made for labeling x-axis of time-line charts with sample dates instead of only sample sequence numbers.

The primary use of seeMAT-A at the projects was to monitor coarse and fine aggregate gradings and fine aggregate fineness modulus, along with monitoring coarse aggregate blends to determine when adjustments in mixture proportions were needed. Tabular reports, including performance analyses, and time-line graphs were the primary features within the program used to analyze the data. Corps personnel acknowledged that seeMAT-A was very helpful in managing the large volume of test data generated at the projects.

7 Laboratory Evaluation of SmartPlant

As stated in Chapter 1 of this report, the overall objective of the investigation was to develop a computer software program, SmartPlant, which will reduce the cost of concrete mixtures and increase construction productivity by minimizing the adverse effects of material and mixture variations upon concrete construction operations. Repeated technical and logistical setbacks prevented Shilstone Software Co. from completing the development of the program in a timely manner. Consequently, only a very abbreviated laboratory evaluation of the program was possible, and no field evaluation of the program could be performed.

Although, as of the date of this report, SmartPlant is still under development, it is now possible to make manual entries into the program and receive suggested adjustments in proportions and batch weights based upon data input.

SmartPlant Evaluation at WES

Between June and September 1992, an abbreviated laboratory evaluation of the concepts to be used in the SmartPlant program was investigated. Since only a very crude version of the program was available at that time, the logic and calculations that would have been performed by SmartPlant were done via manual entries into seeMIX by Mr. James Shilstone, Jr. Aggregates were also blended manually using the seeMAT program. No attempts were made to make mixture adjustments based upon mixture performance history using seeSTAT. However, this operation is also to be designed into the completed SmartPlant program.

Materials and mixtures

Four aggregates were acquired for use in the evaluation. These aggregates had gradings such that extremes of the ASTM C 33 (ASTM 1991a) size designation No. 57 and concrete fine aggregate could be produced by changes in the blends. The coarse aggregates consisted of crushed limestone complying with

the grading requirements of ASTM C 33 (ASTM 1991a) size designations No. 5 (CMD serial No. 920257) and No. 7 (CMD serial No. 920259). Two natural fine aggregates were also used. One of these was masonry sand (CMD serial No. 920260) conforming to the grading requirements of ASTM C 144 (ASTM 1991f), and the other, a very coarse fine aggregate that conformed to the grading requirements of ASTM D 448-86 (ASTM 1991o) size designation No. 9 except that the material finer than the 1.18-mm (No. 16) sieve exceeded the maximum allowable limit by approximately 10 percent. This coarser fine aggregate was termed "grit sand." The aggregate gradings are given in Table 24. The cement used was the same as that used in the seeMIX laboratory evaluation, and its physical and chemical properties are given in Table 1. The same WRA used in the mixtures for the seeMIX laboratory evaluation was also used in the SmartPlant mixtures.

Table 24
SmartPlant Aggregate Gradings

	Cumulative Percent Finer			
Sieve Size	Masonry Sand	Grit Sand	No. 7 Coarse Aggregate	No. 5 Coarse Aggregate
37.0 mm (1-1/2 in.)				100
25.0 mm (1 in.)				89
19.0 mm (3/4 in.)			100	35
12.5 mm (1/2 in.)			91	30
9.5 mm (3/8 in.)		100	61	1
4.75 mm (No. 4)	100	87	11	1
2.36 mm (No. 8)	100	32	2	
1.18 mm (No. 16)	96	21		
600 μm (No. 30)	74	14		
300 μm (No. 50)	30	5		
150 μm (No. 100)	3	1		

The evaluation included the proportioning and production of nine mixtures in the laboratory. Proportioning of these mixtures was proposed and accomplished by Mr. Shilstone, Jr., and production of the mixtures was accomplished at WES by WES staff members. These mixtures formed a 3 × 3 matrix as follows (Table 25):

The numbers in the matrix cells represent mixture designations. For example, mixture 12 represents a mixture whose combined coarse aggregate approaches the coarsest limits permitted by ASTM C 33 (ASTM 1991a) size designation No. 57, and whose fine is approximately the median of the ASTM C 33 fine aggregate

Table 25 SmartPLant Mixture Matrix				
		ASTM C 33 (ASTM 1991a) Size Designation No. 57		
		Coarsest	Median	Fine
ASTM C 33 Fine Aggregate	Coarsest	11	21	31
	Median	12	22	32
	Fine	13	23	33

grading limits. Although all four aggregates were batched in producing the mixtures, the mixtures were proportioned as though one coarse and one fine aggregate were used. To accomplish this Mr. Shilstone, Jr., created separate coarse and fine blends as shown in Table 26.

Table 26
SmartPlant Coarse and Fine Aggregate Blends

Aggregate Type	Blend Type	Masonry Sand percent	Grit Sand percent	No. 7 percent	No. 5 percent
Fine	Fine	100	0	--	--
Fine	Median	75.7	24.3	--	--
Fine	Coarse	58.0	42.0	--	--
Coarse	Fine	--	--	62.0	38.0
Coarse	Median	--	--	41.8	58.2
Coarse	Coarse	--	--	22.0	78.0

Mixtures were then batched and mixed in 0.14-m^3 batches in the laboratory to observe their workability and finishing characteristics. The mixtures provided by Mr. Shilstone, Jr., were proportioned using seeMIX to achieve a slump of approximately 100 mm (4 in.) and an air content of approximately 5.0 percent. This resulted in a water content of 164 kg/m^3 (277 lb/yd^3). However, water was withheld in the laboratory so that the slump of the original and adjusted mixtures was approximately 50 mm (2 in.). The mixture proportions are given in Table 27.

ASTM standard fresh test procedures used to evaluate the mixtures included slump and unit weight. After concrete was tested, it was placed into slab forms; having approximate dimensions of 0.9 × 0.9 m by 100 mm (3 by 3 ft by 4 in.) thick. Concrete was placed in a pile in the center of the forms; then its response to internal vibration was noted. An assessment of its response to vibration was made by measuring the radius of action as described in ACI 309R (ACI 1991c). Compressive strength specimens were also molded and tested at 1, 7, and 28 days.

Table 27
SmartPlant Concrete Mixture Proportions

Mixture	Saturated Surface-Dry Weights, kg/m³ (lb/yd³)								WRA[1]	w/c
	Portland Cement	Coarse F.A Blend	Median F.A. Blend	Fine F.A. Blend	Coarse C.A. Blend	Median C.A. Blend	Fine C.A Blend	Water		
11	329 (554)	795 (1,340)	0	0	1,176 (1,982)	0	0	125 (211)	3.0 (4.0)	0.38
12	329 (554)	0	796 (1,341)	0	1,176 (1,982)	0	0	125 (211)	3.0 (4.0)	0.38
13	329 (554)	0	0	796 (1,342)	1,176 (1,982)	0	0	125 (210)	3.0 (4.0)	0.38
21	329 (554)	795 (1,340)	0	0	0	1,175 (1,981)	0	125 (211)	3.0 (4.0)	0.38
22	329 (554)	0	796 (1,342)	0	0	1,172 (1,976)	0	126 (213)	3.0 (4.0)	0.39
23	327 (552)	0	0	796 (1,342)	0	1,176 (1,982)	0	125 (210)	3.0 (4.0)	0.38
31	329 (554)	795 (1,340)	0	0	0	0	1,176 (1,982)	125 (211)	3.0 (4.0)	0.38
32	329 (554)	0	796 (1,341)	0	0	0	1,176 (1,982)	125 (211)	3.0 (4.0)	0.38
33	329 (554)	0	0	796 (1,342)	0	0	1,176 (1,982)	125 (210)	3.0 (4.0)	0.38

1 Dosage rate is cm^3/1,000 kg cement.

SmartPlant evaluation test results

Results of the fresh tests for the mixtures are shown in Table 28.

Table 28
SmartPlant Fresh Concrete Test Results

Mixture	Slump mm (in.)	Unit Weight kg/m^3 (lb/ft^3)	Radius of Action mm (in.)	Visual Appearance
11	30 (1-1/4)	2,416 (150.8)	125 (5)	Mixture very coarse and harsh; appeared wet but very difficult to rod; did not screed very well, surface torn; some postholing when vibrated; did not close under float.
12	60 (2-1/3)	2,428 (151.6)	100 (4)	Mixture slightly harsh; torn slightly behind screed; consolidated well, but slightly sluggish; closed under float.
13	40 (1-1/2)	2,412 (150.6)	100 (4)	Mixture appeared to have adequate mortar and paste; consolidated well but slightly sticky; torn slightly behind screed; closed under float but dimpled slightly.
21	55 (2-1/4)	2,438 (152.2)	125 (5)	Slightly harsh and grainy, but no segregation noted; torn behind screed and difficult to close under float; appeared to consolidate adequately.
22	50 (2)	2,425 (151.4)	205 (8)	Appeared a little rocky, but consolidated and finished well.
23	50 (2)	2,425 (151.4)	180 (7)	Mixture looked good, rodded easily and consolidated easily; slight postholing, but closed easily as vibrator removed; finished easily.
31	45 (1-3/4)	2,438 (152.2)	125 (5)	Mixture appeared grainy and harsh; acceptable consolidation, but torn behind screed; closed adequately under float.
32	45 (1-3/4)	2,412 (150.6)	125 (5)	Mixture appeared slightly grainy, but consolidated and finished well.
33	45 (1-3/4)	2,432 (151.8)	150 (6)	Mixture postholed slightly when vibrated; torn slightly behind screed, but closed well under float.

Fresh concrete results along with visual observations of the response of the mixtures to vibration and finishing are given in Table 28. This is the same type of information provided in the seeMIX evaluation, but little information is provided with respect to the effectiveness of the SmartPlant program. Proposed adjustments to the aggregate blends were made by Mr. Shilstone, Jr., using seeMAT; however, mixtures were not produced using these mixture adjustments since they would have done little to demonstrate the effectiveness of SmartPlant. A summary of average compressive strength data is given in Table 29. These show that the compressive strengths of those mixtures containing the coarser coarse and fine aggregates generally have slightly larger compressive strengths.

Table 29
SmartPlant Compressive Strength Test Results

Mixture	Compressive Strength, MPa (psi)		
	1-day	7-day	28-day
11	14.8 (2,140)	26.7 (3,870)	37.8 (5,480)
12	17.4 (2,530)	28.1 (4,070)	39.3 (5,700)
13	15.4 (2,240)	25.0 (3,620)	33.8 (4,900)
21	16.1 (2,330)	30.7 (4,450)	38.0 (5,510)
22	15.7 (2,270)	27.6 (4,000)	36.4 (5,280)
23	15.1 (2,190)	28.3 (4,110)	35.9 (5,200)
31	16.3 (2,370)	27.3 (3,960)	38.2 (5,540)
32	15.0 (2,170)	27.6 (4,000)	37.0 (5,370)
33	15.7 (2,280)	25.1 (3,640)	34.9 (5,060)

SmartPlant Evaluation at Alpena Community College

In April 1994, faculty and students at Alpena Community College, Alpena, MI, batched and mixed a series of concrete mixtures under the direction of Mr. Shilstone, Jr. A total of 18 mixtures were proportioned and produced. The first series of mixtures contained nine mixtures similar to those produced for the SmartPlant evaluation conducted at WES. That is, mixtures were proportioned with combinations of coarse and fine aggregates which varied in grading from coarse to fine. The second series of mixtures consisted of adjusted mixtures of the first mixtures. The adjustments were made by SmartPlant such that aggregate proportions were adjusted to bring the combined grading back to a constant, regardless of the original aggregate grading. A summary of these mixtures as provided to WES by Shilstone Software Co. is given in Table 30. The first series of mixtures begins with the numeral "3," and the second series begins with the numeral "4." The mixtures beginning with the numeral "5" were additional mixtures somewhat unrelated to the evaluation. SmartPlant appeared to efficiently use the seeMIX and seeMAT-A features to make these adjustments. Compressive strength specimens were molded during the evaluation. The results of these tests conducted at 1, 3, 7, and 28 days indicated that the compressive strengths of the adjusted mixtures may be slightly less than the original mixtures at all ages. However, Shilstone noted that numerous weighing errors were made in the production of concrete and stated that this may have accounted for the apparent lack of uniformity in the adjusted mixtures. The average compressive strengths were graphically presented to WES by Shilstone Software Co., as shown in Figure 29.

Table 30
Alpena Concrete Mixtures

	Material weights, kg/m^3 (lb/yd^3)					
Mix ID	Cement	Water	#57 Stone	#8 Stone	2NS Sand	Mason Sand
3-14	335 (565)	193 (325)	1,125 (1,897)	0	759 (1,280)	0
3-15	335 (565)	193 (325)	1,125 (1,897)	0	489 (824)	271 (456)
3-16	335 (565)	193 (325)	1,125 (1,897)	0	167 (282)	592 (998)
3-24	335 (565)	193 (325)	968 (1,632)	159 (268)	759 (1,280)	0
3-25	335 (565)	193 (325)	968 (1,632)	159 (268)	489 (824)	271 (456)
3-26	335 (565)	193 (325)	968 (1,632)	159 (268)	167 (282)	592 (998)
3-34	335 (565)	193 (325)	855 (1,442)	272 (459)	759 (1,280)	0
3-35	335 (565)	193 (325)	855 (1,442)	272 (459)	489 (824)	271 (456)
3-36	335 (565)	193 (325)	855 (1,442)	272 (459)	167 (282)	592 (998)
4-14	335 (565)	193 (325)	1,076 (1,813)	0	810 (1,365)	0
4-15	335 (565)	193 (325)	1,156 (1,948)	0	469 (791)	259 (437)
4-16	335 (565)	193 (325)	1,230 (2,073)	0	144 (242)	510 (860)
4-24	335 (565)	193 (325)	896 (1,510)	147 (248)	844 (1,423)	0
4-25	335 (565)	193 (325)	968 (1,632)	159 (268)	489 (824)	271 (456)
4-26	335 (565)	193 (325)	1,035 (1,745)	159 (268)	150 (252)	530 (894)
4-34	335 (565)	193 (325)	775 (1,306)	247 (416)	867 (1,461)	0
4-35	335 (565)	193 (325)	838 (1,413)	267 (450)	504 (849)	282 (475)
4-36	335 (565)	193 (325)	899 (1,515)	286 (482)	154 (260)	548 (923)
5-1	335 (565)	193 (325)	781 (1,316)	354 (596)	573 (965)	181 (305)
5-2	335 (565)	193 (325)	692 (1,167)	314 (529)	829 (1,398)	53 (89)
5-3	335 (565)	193 (325)	405 (683)	720 (1,214)	173 (292)	592 (998)

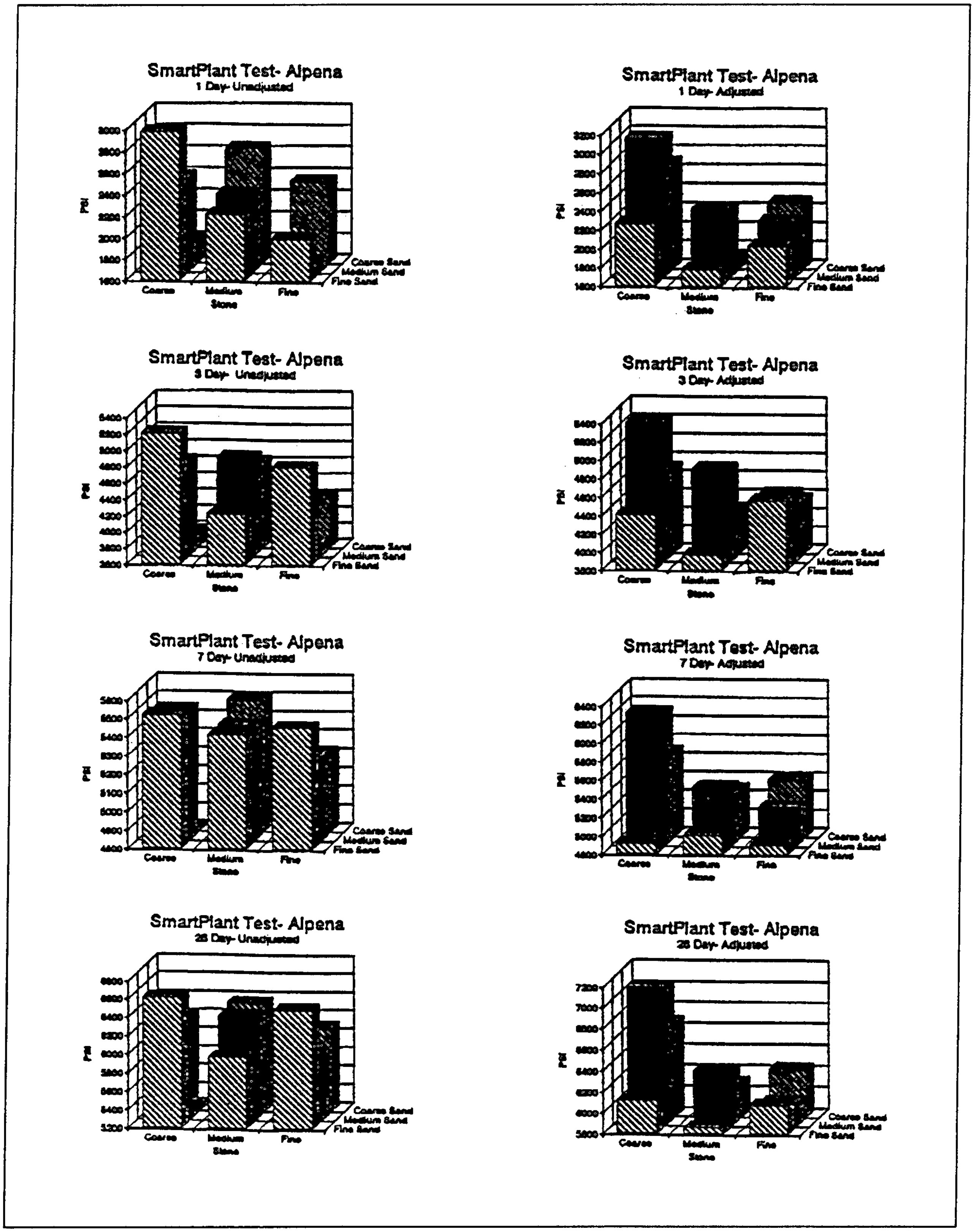


Figure 29. Average compressive strengths at 1, 3, 7, and 28 days

8 Conclusions and Recommendations

Conclusions

SeeMIX evaluation

The results of the laboratory and field evaluations on the use of seeMIX for proportioning concrete mixtures for optimum fresh and hardened properties indicated the following:

a. No provisions are currently made in seeMIX for proportioning mass concrete mixtures having 75-mm (3-in.) or greater NMSA. When the principles of seeMIX were used to proportion lean mass concrete mixtures, it was obvious that the resulting mixtures were very harsh and that placement and consolidation of the mixtures would be very difficult. The increase in the volume of intermediate aggregate sizes in these mixtures apparently increased the particle surface area and resulting mortar demand to the extent that 0.44 m^3 (12.0 ft^3) of mortar recommended by ACI 211.1 (ACI 1991a) for 75-mm (3-in.) NMSA was inadequate. Only after the mortar content was increased to 0.48 m^3 (13.0 ft^3) was the mixture containing aggregate graded to match the 0.45 power curve judged to be workable. There was no appreciable improvement in the compressive strength of the six mixtures proportioned over the reference mixture which was proportioned according to the guidelines given in ACI 211.1 (ACI 1991a). Therefore, a simple extrapolation of the existing seeMix principles to include larger aggregate sizes is not appropriate. Further development of seeMix is needed if mass mixtures containing aggregates larger than 37.5 mm (1-1/2 in.) are to be proportioned. The effectiveness of seeMix in proportioning mass mixtures containing aggregates 37.5 mm (1-1/2 in.) or smaller was not determined.

b. Paving mixtures proportioned using seeMIX and the 0.45 power grading curve were workable and had fresh concrete properties comparable to those proportioned to ACI 211.1 (ACI 1991a). The compressive and flexural strengths of the seeMIX mixtures were not generally greater than

the reference mixture; however, the underwater abrasion resistance and the resistance to chloride ion penetration for the seeMIX mixtures were somewhat improved. This may have been the result of a more uniform aggregate particle distribution throughout the seeMIX mixtures.

c. One of the structural mixtures proportioned using seeMIX was judged to be as workable as the reference structural mixture proportioned according to ACI 211.1 (ACI 1991a), even though the seeMIX mixture had lower water and cementitious materials contents. This seems to indicate that the richer concrete mixtures are perhaps better suited to the proportioning concepts advocated by Shilstone than the leaner mixtures such as might be used in mass concrete.

d. The field evaluations conducted on seeMIX reemphasized that it should be considered for use on richer mixtures such as paving and structural concrete mixtures. The Blue River Paved Reach investigation indicated that seeMIX mixtures were at least as workable, if not more so, than the original proposed mixture and the underwater abrasion resistance and compressive strength was improved. However, it was necessary to increase the water and cementitious material contents of the seeMIX mixture to achieve these results. Nonetheless, the improved aggregate particle distribution of the seeMIX was likely the predominant reason for improved underwater abrasion resistance. Results of the Richmond Road evaluation indicated that the paving mixture proportioned using the seeMIX program was as workable as the reference mixture having the same water and cementitious material contents, but the seeMIX mixture had higher compressive and flexural strengths. Based upon a qualitative analysis of cores, this mixture also appeared to have smaller entrapped air-voids than the reference mixture. This may have been the result of a combined aggregate that was well-graded as compared to that of the reference mixture.

SeeMAT-A, -C, and -P reviews

With these programs, the management of test data needed to adjust mixture proportions in seeMIX and ultimately in SmartPlant. Each of the programs provides the means to generate useful reports and to statistically analyze test data. These features make the programs useful as stand-alone quality-control and quality-assurance tools. The principal strength of the programs is that they provide predefined user fields data storage and analysis combined with predefined plotting and printing features. This obviates the need to adapt other software such as spreadsheets and graphics packages to this purpose by combining some of the features of each into a single program. Three perceived deficiencies of seeMAT-C and -P include the listing of material as passing the 45-μm (No. 325) sieve, the inclusion of "R-value," and the incorrect calculation Al_2O_3. These appear to be relatively minor deficiencies that should be able to be corrected relatively easily. SeeMAT-A has an aggregate blending feature which is useful for combining aggregates for use in seeMIX or for use as a quality-assurance tool. This

program received good reviews at both the Gray's Landing and Point Marion resident offices and was used effectively to monitor aggregate test data and to periodically reblend coarse aggregates to match the ACI 211.1 (ACI 1991a) maximum density grading.

SmartPlant evaluation

One of the tasks in this CPAR project was to conduct a thorough evaluation of the SmartPlant program. Early in the investigation, it was agreed by both WES and Shilstone Software Co. that the best way to accomplish this task was through a field evaluation in which the SmartPlant program could be used extensively for an extended period of time. This type of evaluation would permit the continued production of concrete so that effects of mixture adjustments could be observed. The evaluation would have enabled WES and Shilstone Software Co. to determine how the program reacted to material changes as well as changes in fresh and hardened concrete test results.

This type of evaluation was not conducted due to numerous logistical and technical problems encountered by Shilstone Software Co. Laboratory evaluations of the program were conducted, but these evaluations monitored only the effects of adjustments made to concrete mixtures whose aggregate gradings were forced to vary widely. The adjustments made at Alpena Community College were based upon data entered manually into SmartPlant. This exercise did at least indicate that SmartPlant sensed the need for mixture adjustments due to aggregate grading changes and could use the appropriate features of seeMAT-A and seeMIX to make suggested adjustments. This was an important step in the development and evaluation of the program, but only a small first step. The full range of the program was not tested manually, since no data were entered into SmartPlant and processed by seeMAT-C or seeSTAT so that other adjustments to the mixture proportions could be observed.

During this investigation, Shilstone Software Co. made extensive efforts to transfer SmartPlant technology to the public and private sectors via publication of papers, presentations, seminars, workshops, and industry shows. Figures G1 and G2, Appendix G, list the technical articles and technology transfer functions, respectively, prepared under authority of this CPAR project. For information purposes, a tabulation of the sales of SmartPlant component software (i.e. seeMIX, seeSTAT, and seeMAT-A) by state is given in Figure G3 for the period 1989-1995. This figure indicates that during this time, 511 copies of seeMIX, 395 copies of seeSTAT, and 357 copies of seeMAT-A were sold.

Recommendations

The primary objective of this CPAR project was to develop a computer software program, SmartPlant, which would reduce the cost of concrete mixtures, increase concrete construction productivity, and improve infrastructure durability. The software was to accomplish these goals by minimizing the adverse effects of

material and mixture variations upon concrete construction operations. As of the date of this report, giant steps have been taken toward the accomplishment of the project objective, but it has yet to be completed. Component programs have been developed which, individually, perform some of the tasks necessary to improve various aspects of concrete construction productivity. The new mixture proportioning concepts proposed under the seeMIX program can be cited as a major accomplishment. Because of the diligent efforts of Shilstone Software Co., both ASTM and ACI have taken steps which have enabled industry to readily take advantage of the proportioning concepts.

However, SmartPlant has yet to be fully evaluated in the laboratory or the field. It is recommended that both extensive laboratory and field evaluations are needed to effectively commercialize SmartPlant. The laboratory evaluation should be done under controlled conditions, preferably using full-scale batching and mixing equipment. The testing plan followed in the CPAR evaluation, whereby variations in materials test data were artificially introduced should be followed again. Variations in fresh and hardened concrete properties should also be introduced to evaluate how effectively SmartPlant uses seeSTAT and seeMIX programs. The laboratory evaluation should be conducted using a variety of aggregates and cementitious materials and should be designed experimentally so that sound statistical judgments regarding the effectiveness of the program can be made.

A minimum of one field evaluation of the completed program, operating as automatically as possible is needed to discover design deficiencies. The duration of the field evaluation(s) should be sufficient to determine how the program operates under regular and prolonged production. It should also be long enough to evaluate how SmartPlant accounts for the normal commercial variations experienced in aggregates and cementitious materials. After objective laboratory and field evaluations of SmartPlant are completed, deficiencies can be corrected and commercialization may earnestly begin.

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c. Standard test method for unit weight, yield, and air content (gravimetric) of concrete," Designation: C 138-81.

d. "Standard test method for compressive strength of cylindrical concrete specimens," Designation: C 138-86.

e. "Standard test method for slump of hydraulic cement concrete," Designation: C 143-90.

f. "Standard specification for aggregate for masonry mortar," Designation: C 144-89.

g. "Standard specification for portland cement," Designation: C 150-89.

h. "Standard test method for sampling freshly mixed concrete," Designation: C-172.

i. "Standard test method for air content of freshly mixed concrete by the pressure method," Designation: C 231-91.

j. "Standard test methods for bleeding of concrete," Designation: C 232-87.

k. Standard specification for air-entraining admixtures for concrete," Designation: C 260-86.

l. "Standard specification for blended hydraulic cements," Designation: C 595-89.

m. "Standard specification for fly ash and raw or calcined natural pozzolan for use as a mineral admixture in portland cement concrete," Designation: C 618-91.

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Appendix A Test Method for Two-Point Workability (Wykeham Farrance)[1]

[1] Complete references are listed following main text.

Scope

This test method covers a procedure for measuring rheological properties of concrete by measuring the amount of torque required to turn an impeller in the concrete at varying speeds. The assembled apparatus is shown in Figure A1.

Applicable Documents

Applicable American Society for Testing and Materials Standards are:

C 143 Method for slump of hydraulic cement concrete (ASTM 1991e)
C 172 Method of sampling freshly mixed concrete (ASTM 1991h)
C 231 Method for air content of freshly mixed concrete by the pressure method (ASTM 1991i)

Apparatus

Two-point apparatus

The drive system shall have a ½-hp electric motor operating through an infinitely variable hydraulic transmission and a 4.75:1 worm-and-pinion right-angled reduction gear. All parts shall be mounted on a simple frame, fabricated from a steel angle section, and provided with adjustable feet for leveling and castors for ease of movement. A 0- to 1,000-psi pressure gauge, suitably mounted to reduce the effects of vibration shall be connected to the gear box. A snubber shall be included in the hydraulic line to reduce oscillations. A rack-and-pinion gear shall be provided to raise and lower the concrete bowl. The system is shown in Figure A2.

Impeller

The impeller shall be made from flat blades fixed in a helical thread cut in the central shaft in a manner that permits concrete to fall back through the gaps. The interrupted helical screw is shown in Figure A3.

Bowl

The bowl shall be a metal container not readily attached by the cement paste. The bowl shall be of the dimensions shown in Figure A3.

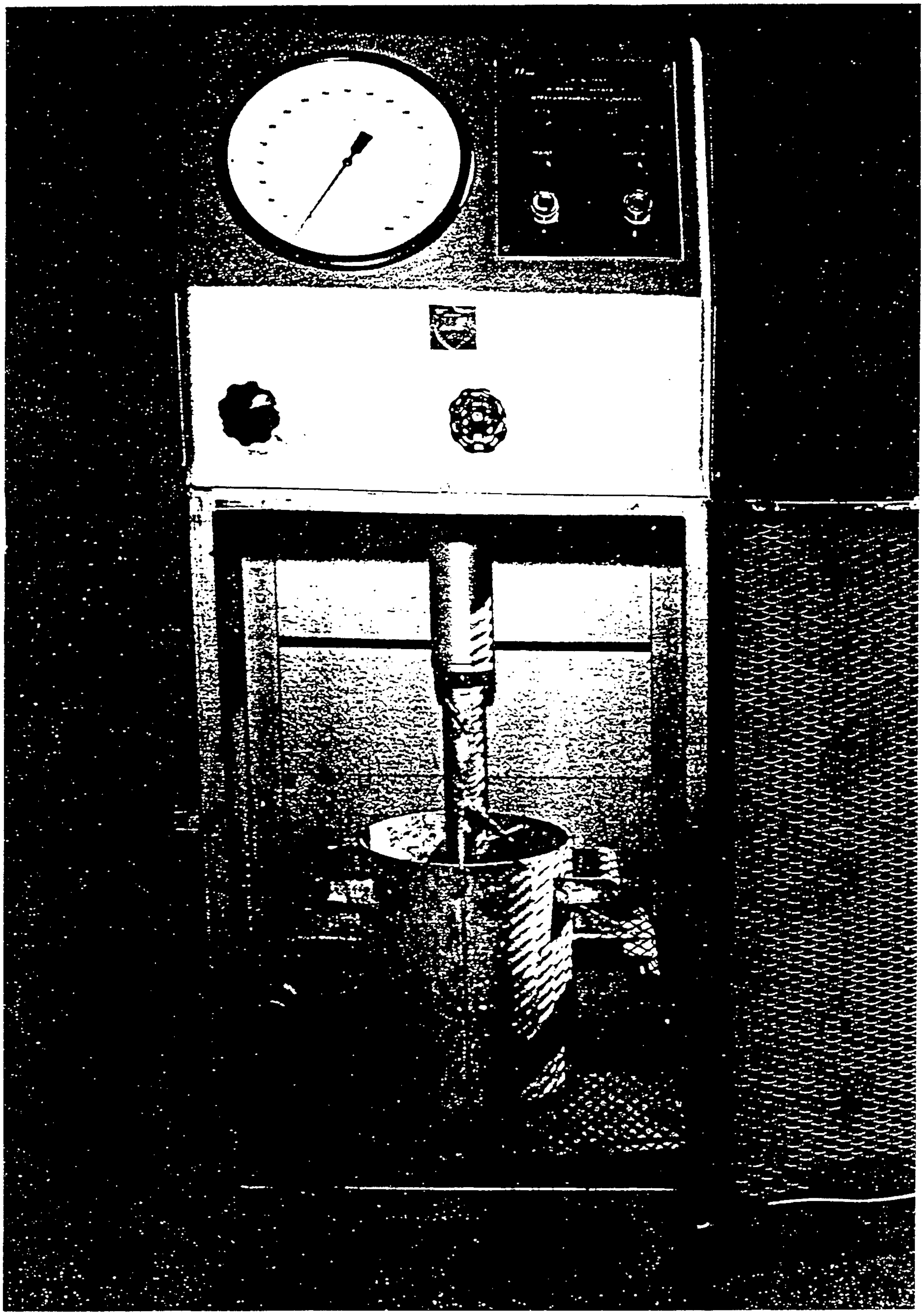


Figure A1. Assembled two-point apparatus

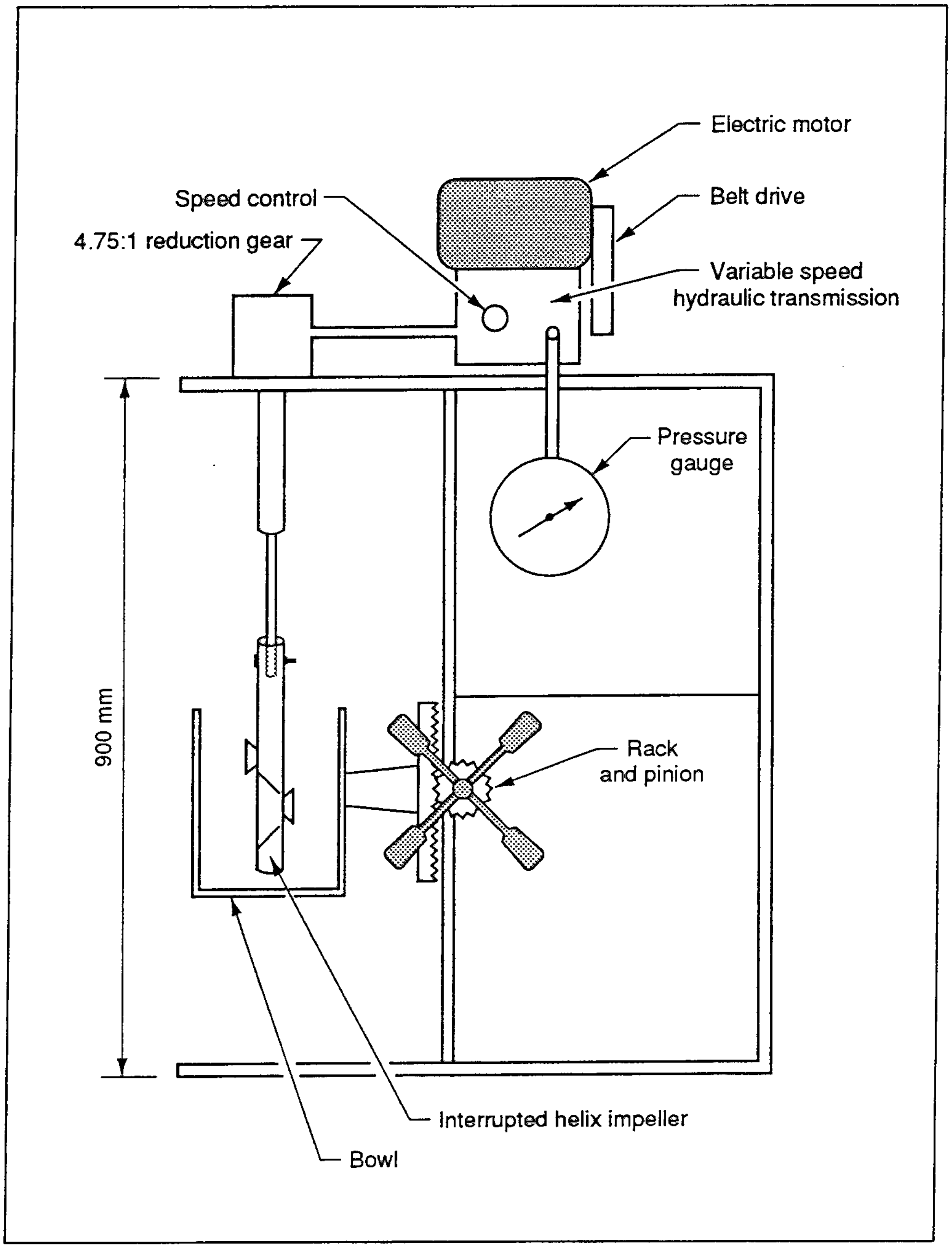


Figure A2. Two-point apparatus (after Tattersall and Banfill 1983)

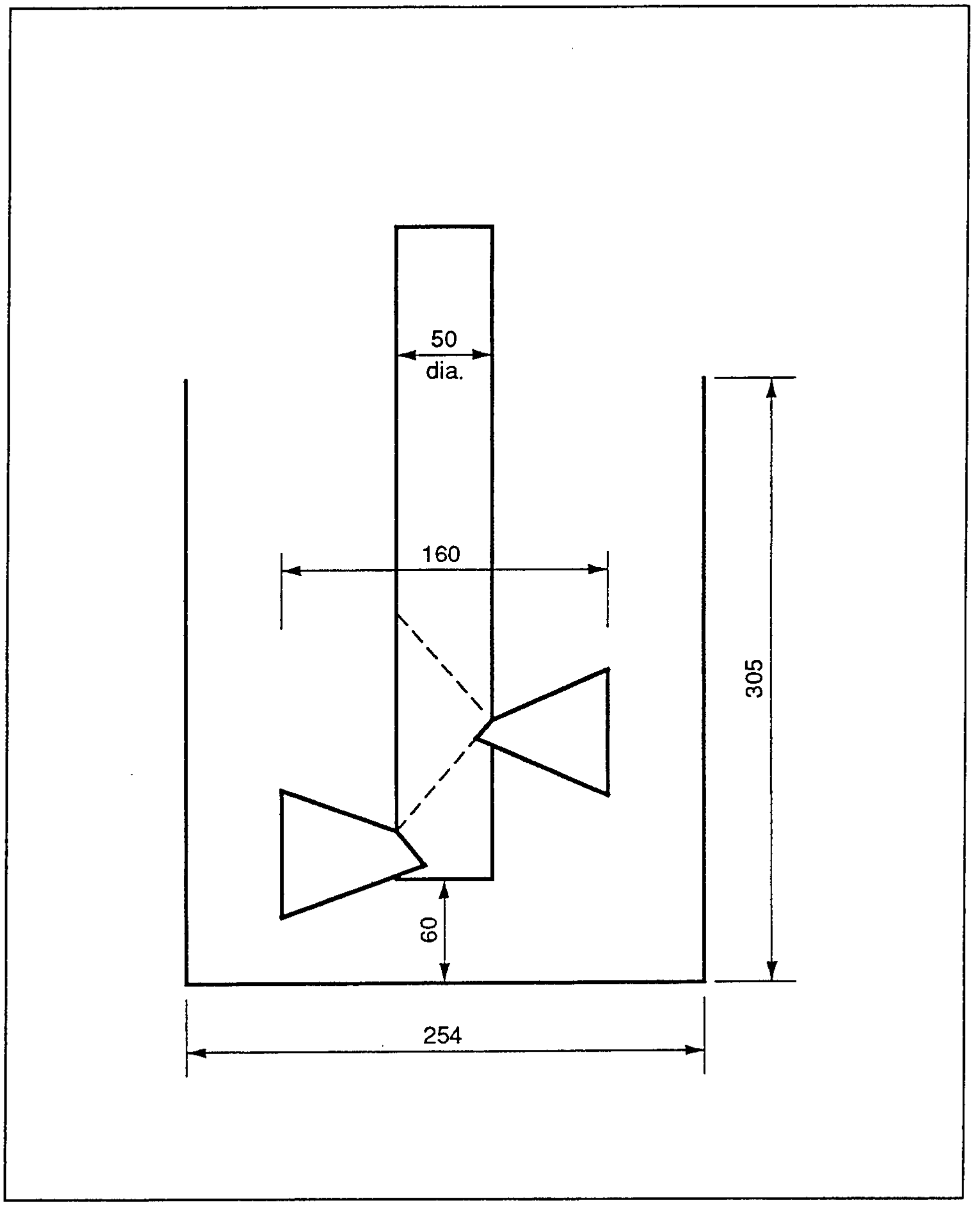


Figure A3. Helical screw and bowl (dimensions are in millimetres) (after Tattersall and Banfill 1983)

Sample

The sample of concrete shall be representative of the entire batch and shall be obtained in accordance with Method C 172. If the concrete contains coarse aggregate particles that would be retained on a 37.5-mm (1-1/2-in.) sieve, a representative sample should be wet seived over a 37.5-mm (1-1/2-in.) sieve to yield somewhat more than enough to fill the bowl to the desired level. The wet sieving procedure is described in Method C 172.

Procedure

Preparation of the apparatus

Prepare the apparatus for testing as follows:

a. Fill and bleed the hydraulic system and fill the reduction gear box.

b. Check that the speed control unit is correctly zeroed.

c. Check that brass snubber valve and the valve in the hydraulic line are set correctly.

d. Set speed at 2 rps with impeller rotating anticlockwise and allow apparatus to warm up for about 30 min.

Measure workability

Measure workability as follows:

a. Fit helical impeller to shaft and fit 254-mm bowl.

b. Raise bowl to working position, this is when the center of the impeller shaft is 60 mm above the bottom of the bowl.

c. Set speed at 0.50 rps with the impeller rotating anticlockwise.

d. Fill bowl, gradually, with concrete to 75 mm from the rim, at the same time keeping an eye on the rise in pressure so the machine is not overloaded.

e. Increase speed setting and allow time for pressure to stabilize.

f. Read speed on tachometer.

g. Read pressure gauge; large oscillations due to trapping of the aggregates should be ignored and an average position of the needle for the small oscillations should be recorded.

h. The speed and pressure are then recorded at seven different speeds.[1]

i. Record the idling pressures with the bowl removed at the speeds used in subparagraph *h*.

Calculation of results

Calculation of results is best shown by means of the following worked example. The test was carried out on a mixture having an aggregate-cement ratio of 4-1/2:1, 40-percent fines, and 100-mm slump. The calibration coefficient for the apparatus was 0.0215.

The experimental results are tabulated as follows:

Pressure Gauge Readings

Speed Setting	Speed (rpm)	Total Pressure	Idling Pressure	Net Pressure	Impeller Speed (rps)	Comments
4	380	410	150	260	1.33	5.58
3-1/2	347	386	145	241	1.22	5.17
3	300	363	140	223	1.05	4.79
2-1/2	250	335	133	200	0.88	4.29
2	200	312	130	182	0.70	3.91
1-1/2	147	290	125	165	0.52	3.54
1	95	265	120	143	0.33	3.07

For the above table of figures the CORRELATION COEFFICIENT (r) = 0.998
SLOPE (h) .... = 2.45
INTERCEPT (g)......................... = 2.23

The calculation can be carried out easily with any inexpensive calculator capable of regression analysis.

[1] For practical site or plant work, it is normally sufficient to take readings at four speeds only. (The experimental error will be somewhat greater.)

Calculation of Errors

Error on h

Select line on graph in Figure A4 corresponding to number of experimental points. In this case, $n=7$. Knowing correlation coefficient (in this case, 0.998), read off error on h. In this case, it is approximately 5 percent.

Error on g

Multiply error on h by $0.95 \ \frac{h}{g}$

In this case error on $g = 0.95 \times \frac{2.45}{2.23} \times 5 = 5\%$

Results

The report shall include the following data as are pertinent to the variables studied in the tests:

a. **Properties of concrete mixture:**

(1) Type and proportions of cement, fine aggregate, coarse aggregate, water-cement ratio, and sand-aggregate ratio.

(2) Kind and proportions of any addition or admixture used.

(3) Air content of fresh concrete.

(4) Slump of fresh concrete.

b. **Two-point workability:**

(1) Pressure measurements at a minimum of two speed settings (note 2) with the impeller inserted into the concrete.

(2) Pressure measurements at the same speed settings as used with the impeller not inserted into the concrete.

(3) Calibration coefficient (supplied by the manufacturer for each machine).

(4) Torque value as calculated from the pressure measurements.

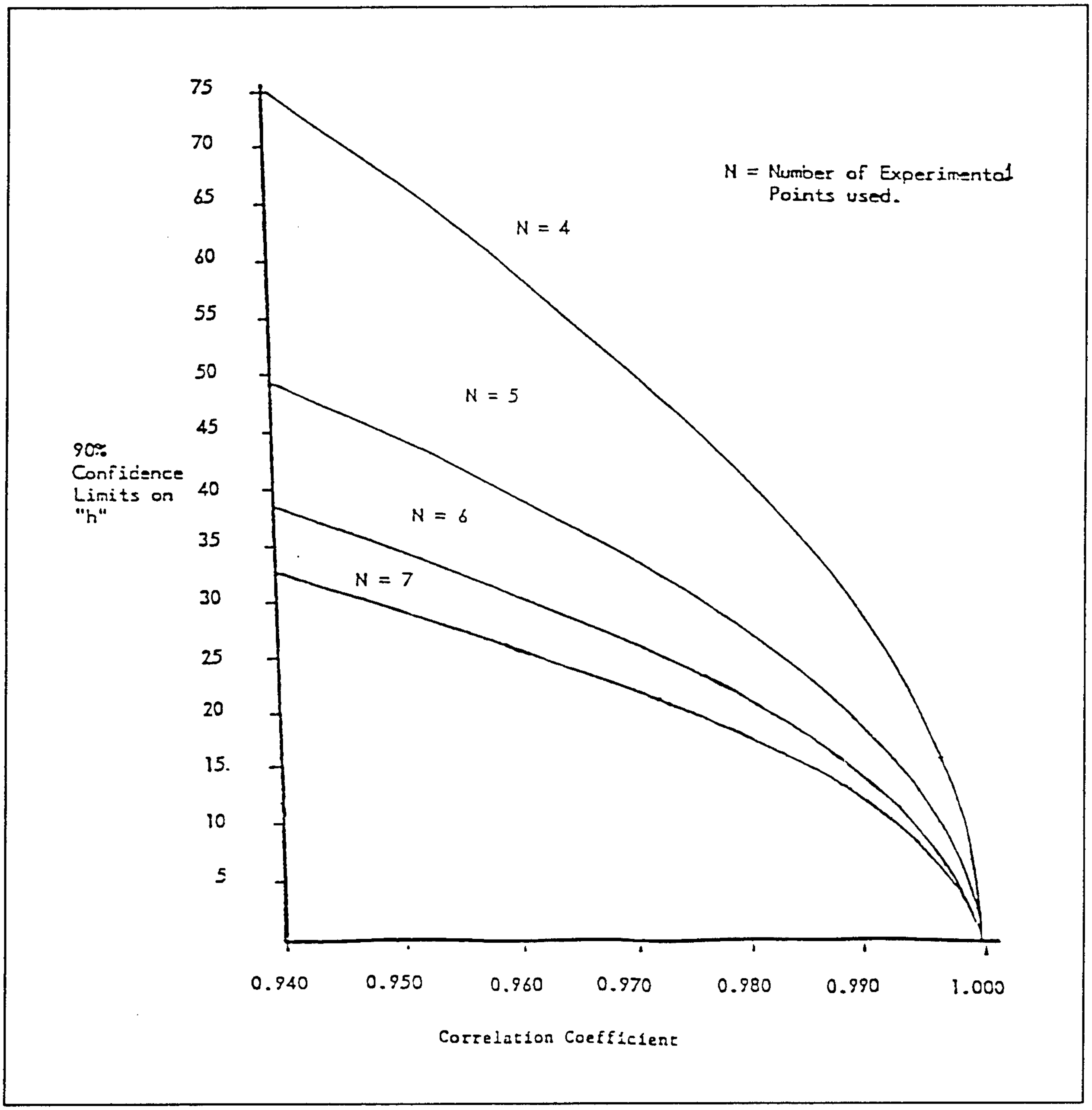


Figure A4. Relationship between 90-percent confidence limits on "h," number of experimental points, and correlation coefficient (reprinted by permission of Wykeham Farrance)

(5) Plotted values of torque versus speed, with torque being on the x-axis and speed being on the y-axis.

(6) The correlation coefficient of the linear regression line through the torque versus speed points.

(7) The x-intercept (g) representing the yield value.

(8) The inverse of the slope of the line (h).

Additional points will better define the line. Experiments have shown probable error in plotting the line reduces significantly when the number of measurements is increased, up to approximately seven.

Testing of Low-Workability Concretes

To test low-workability concretes, it is necessary to use an impeller of a different shape and to cause that impeller to rotate in planetary motion. The equipment to make this modification is available as an optional extra. In this modified form, the apparatus has been used successfully in the laboratory and onsite for concretes with a slump as low as 25 mm. However, difficulties are sometimes experienced, and it is recommended that for any particular application preliminary trials should be carried out. The basic test procedure and the calculation of results are the same as for the standard apparatus, so only the modification and differences will be listed.

a. Remove the 4.75:1 reduction gear and replace with the 20:1 reduction gear and fit the planetary motion unit to the impeller shaft.

b. Fit the H-shaped impeller to the shaft on the planetary unit.

c. Fit the 356-mm bowl instead of the 254-mm bowl.

d. The working clearance is 90 mm from the center of the shaft to the bowl.

e. Fill the bowl to 140 mm from the rim (45 kg of concrete, approximately).

f. Use as many as seven different speed settings.

Because of the use of planetary motion, the oscillations of pressure readings are somewhat worse, and correspondingly the correlation coefficients obtained are somewhat lower than when uniaxial rotation is used. Consequently, the experimental errors on g and h are larger. By suitable calibration with materials of known rheological properties, it is possible to interrelate the results from the two forms of machine. As a rough guide, it may be said that the values of g obtained from the two forms of apparatus are about the same but the value of h obtained with the H-shaped impeller in planetary motion is about 30 percent higher than that obtained with the helical impeller in uniaxial motion.

Appendix B
Individual Test Results for Slump, Unit Weight, Air Content, Bleed, Vebe Consistency Time, and Compressive Strength — SeeMIX Laboratory Evaluation

Table B1
Mass Concrete Test Results

Mixture	Batch No.	Slump mm (in.)	Unit Weight kg/m^3 (lb/ft^3)	Air Content percent	Bleed percent	Vebe time sec	Compressive Strength, MPa (psi)	
							28-day	90-day
MASS	1	40 (1-1/2)	2,345 (146.4)	5.2	3.5	2.5	20.1 (2,920), 19.5 (2,830), 20.3 (2,940)	25.2 (3,660), 26.8 (3,890), 25.7 (3,730)
	2	30 (1-1/4)	2,355 (147.0)	5.0	3.6	2.3	20.6 (2,990), 19.9 (2,880), 19.8 (2,870)	27.0 (3,910), 27.2 (3,940), 28.3 (4,100)
MASS-2	1	25 (1)	2,390 (149.2)	4.4	3.6	4.4	20.3 (2,940), 19.0 (2,760), 19.2 (2,780)	26.2 (3,800), 25.6 (3,710), 25.0 (3,630)
	2	15 (1/2)	2,403 (150.0)	4.3	3.4	10.8	20.8 (3,010), 21.1 (3,060), 20.5 (2,970)	28.5 (4,140), 28.7 (4,160), 28.8 (4,170)
MASS-3	1	15 (1/2)	2,396 (149.6)	4.9	3.8	3.3	17.1, (2,480), 16.8 (2,440), 16.6 (2,410)	23.9 (3,470), 23.0 (3,330), 23.7 (3,430)
	2	5 (1/4)	2,384 (148.8)	5.2	3.5	4.5	17.3 (2,510), 16.6 (2,410), 17.1 (2,480)	24.1 (3,500), 23.4 (3,400), 24.9 (3,610)
MASS-21	1	20 (3/4)	2,352 (146.8)	5.6	5.3	2.1	17.2 (2,490), 17.9 (2,600) 17.4 (2,530)	22.6 (3,270), 21.9 (3,180), 22.2 (3,220)
	2	15 (1/2)	2,377 (148.4)	4.6	4.5	6.5	20.0 (2,900), 19.8 (2,870), 19.2 (2,790)	21.2 (3,070), 20.3 (2,940), 20.5 (2,970)
MASS-31	1	5 (1/4)	2,390 (149.2)	4.0	4.9	4.6	20.3 (2,940), 19.8 (2,870), 20.0 (2,900)	20.5 (2,970), 21.6 (3,130), 21.4 (3,110)
	2	25 (1)	2,387 (149.0)	4.6	5.6	3.0	20.3 (2,940), 19.4 (2,810), 19.5 (2,830)	20.7 (3,000), 21.2 (3,070), 20.9 (3,030)
MASS-32	1	30 (1-1/4)	2,371 (148.0)	4.7	6.0	5.0	17.8 (2,580), 16.7 (2,420), 17.7 (2,560)	23.7 (3,430), 23.2 (3,360), 21.6 (3,130)
	2	45 (1-3/4)	2,345 (147.6)	4.6	5.2	2.0	21.4 (3,100), 20.5 (2,970), 19.8 (2,870)	27.7 (4,010), 28.5 (4,140), 26.7 (3,870)
MASS-4	1	40 (1-1/2)	2,345 (146.4)	5.5	5.5	3.5	20.0 (2,900), 21.0 (3,040), 20.8 (3,010)	27.1 (3,930), 27.1 (4,070), 27.0 (3,910)
	2	30 (1-1/4)	2,358 (147.2)	5.1	3.7	3.7	18.7 (2,710), 19.5 (2,830), 19.7 (2,850)	26.5 (3,840), 24.4 (3,540), 24.0 (3,480)

Table B2
Fresh Paving Concrete Test Results

Mixture	Batch No.	Slump mm (in.)	Unit Weight kg/m^3 (lb/ft^3)	Air Content percent	Bleed percent	Vebe time sec
PAVE-1	1	50 (2)	2,358 (147.2)	5.6	1.6	2.7
	2	40 (1-1/2)	2,371 (148.0)	5.1	1.2	3.0
PAVE-2	1	40 (1-1/2)	2,380 (148.6)	5.0	1.8	3.1
	2	40 (1-1/2)	2,384 (148.8)	5.0	1.3	3.1
PAVE-3	1	55 (2-1/4)	2,358 (147.2)	5.6	1.2	1.7
	2	55 (2-1/4)	2,345 (146.4)	6.2	1.4	2.0
PAVE-4	1	3 (75)	2,319 (144.8)	6.8	1.2	1.5
	2	90 (3-1/2)	2,307 (144.0)	6.9	1.3	1.7
PAVE-5	1	65 (2-1/2)	2,339 (146.0)	6.3	1.6	2.3
	2	65 (2-1/2)	2,351 (146.8)	5.7	1.8	2.0
PAVE-31	1	50 (2)	2,345 (146.4)	5.8	1.1	1.9
	2	45 (1-3/4)	2,358 (147.2)	5.6	2.1	1.9
PAVE-41	1	30 (1-1/4)	2,370 (148.0)	4.8	1.5	2.0
	2	25 (1)	2,364 (147.6)	4.9	1.6	2.3
PAVE-51	1	30 (1-1/4)	2,352 (146.8)	5.3	1.6	2.4
	2	45 (1-3/4)	2,339 (146.0)	5.8	1.2	2.1
PAVE-6	1	45 (1-3/4)	2,345 (146.4)	5.4	2.7	1.7
	2	50 (2)	2,352 (146.8)	5.4	2.7	1.9

Table B3
Hardened Paving Concrete Test Results

Mixture	Batch No.	Compressive Strength, MPa (psi)		Flexural Strength, MPa (psi)		Charged Passed coulombs
		7-day	28-day	7-day	28-day	
PAVE-1	1	24.1 (3,500), 24.4 (3,540), 23.2 (3,370)	30.3, (4,390), 30.1 (4,360), 30.0 (4,350)	4.05 (590), 4.20 (610)	5.25 (760), 4.95 (720)	2,598
	2	26.8 (3,890), 30.1 (4,370), 28.7 (4,160)	33.3 (4,830), 33.7 (4,880), 32.5 (4,720)	4.10 (595), 4.05 (585)	4.35 (630), 4.30 (625)	2,446
PAVE-2	1	23.5 (3,410), 24.9 (3,610), 23.2 (3,360)	31.2 (4,530), 30.5 (4,420), 30.8 (4,470)	4.25 (615), 4.40 (640)	4.50 (665), 5.05 (730)	2,383
	2	23.4 (3,400), 24.2 (3,510), 22.8 (3,310)	29.8 (4,320), 30.0 (4,350), 31.0 (4,490)	4.70 (685), 4.25 (620)	5.35 (775), 4.85 (705)	2,183
PAVE-3	1	21.9 (3,180), 22.9 (3,320), 22.8 (3,310)	28.4 (4,120), 27.9 (4,050), 28.5 (4,140)	5.35 (775), 4.95 (720)	4.65 (675), 4.35 (630)	--[1]
	2	22.7 (3,290), 21.0 (3,040), 23.6 (3,420)	27.8 (4,030), 28.7 (4,160), 28.5 (4,140)	3.85 (555), 4.05 (590)	4.75 (690), 4.65 (675)	--
PAVE-4	1	21.4 (3,100), 20.5 (2,970), 21.2 (3,080)	25.4 (3,680), 24.8 (3,590), 24.9 (3,610)	4.15 (605), 4.20 (610)	5.05 (730), 4.55 (660)	--
	2	21.2 (3,080), 20.8 (3,010), 20.1 (2,920)	26.0 (3,770), 23.7 (3,430), 25.7 (3,730)	3.60 (525), 3.85 (555)	3.95 (575), 4.45 (645)	--
PAVE-5	1	22.6 (3,270), 22.4 (3,250), 22.3 (3,240)	29.5 (4,280), 28.1 (4,070), 28.8 (4,170)	4.10 (595) 4.40 (640)	5.25 (765), 5.05 (735)	--
	2	23.2 (3,360), 23.3 (3,380), 22.4 (3,250)	29.7 (4,300), 29.2 (4,240), 29.5 (4,280)	4.50 (655), 4.25 (620)	4.75 (690), 4.70 (685)	--
PAVE-31	1	21.7 (3,150), 21.6 (3,130), 21.4 (3,110)	28.5 (4,140), 27.7 (4,010), 27.0 (3,910)	3.90 (565), 3.95 (570)	4.60 (670), 4.50 (655)	2,288
	2	24.6 (3,570), 24.4 (3,540), 24.0 (3,480)	31.0 (4,490), 31.2 (4,530), 32.2 (4,670)	4.25 (615), 4.50 (655)	5.65 (820), 5.40 (785)	2,178
PAVE-41	1	23.9 (3,470), 24.1 (3,500), 24.9 (3,610)	31.9 (4,620), 32.5 (4,720), 31.9 (4,630)	4.25 (615), 4.00 (580)	4.60 (670), 5.30 (770)	--
	2	26.2 (3,800), 24.6 (3,570), 26.1 (3,780)	31.9 (4,620), 33.0 (4,780), 31.4 (4,550)	4.55 (660), 4.30 (625)	5.20 (760), 4.60 (670)	--
PAVE-51	1	21.9 (3,180), 23.0 (3,330), 24.4 (3,540)	29.9 (4,330), 30.3 (4,400), 30.8 (4,460)	3.95 (570), 4.00 (580)	4.50 (650), 4.65 (675)	--
	2	23.7 (3,430), 21.4 (3,110), 21.9 (3,180)	31.1 (4,510), 30.1 (4,370), 29.7 (4,300)	3.90 (565), 4.15 (600)	4.70 (685), 5.15 (745)	--
PAVE-6	1	24.1 (3,500), 25.7 (3,730), 25.6 (3,710)	31.4, (4,560), 31.6 (4,580), 31.7 (4,600)	3.95 (570), 4.85 (700)	5.60 (815), 5.50 (800)	2,563
	2	24.4 (3,540), 23.8 (3,450), 23.9 (3,470)	29.5 (4,280), 31.1 (4,510), 31.4 (4,550)	4.50 (655), 4.20 (610)	5.25 (765), 5.00 (725)	2,467

[1] -- indicates test not conducted for this batch

Table B4
Paving Concrete Underwater Abrasion Test Results

Mixture	Specimen No.	Cumulative Volume Loss, 10^{-4} m^3					
		12 hr	24 hr	36 hr	48 hr	60 hr	72 hr
PAVE-1	11	1.99	3.34	5.21	6.60	7.82	8.39
	21	2.00	3.63	5.13	6.67	8.33	9.06
	31	1.39	2.88	4.20	5.51	6.72	7.25
PAVE-2	21	1.94	2.64	4.62	6.13	7.74	9.43
	22	1.51	3.03	4.58	6.17	7.65	7.98
	23	1.36	2.69	4.12	5.43	6.66	6.52
PAVE-31	311	2.26	3.31	4.55	5.43	6.34	7.56
	312	2.81	3.01	4.52	5.55	6.65	7.09
	313	0.58	2.58	4.34	5.16	6.01	7.19
PAVE-6	61	1.14	2.23	3.55	5.28	6.26	8.49
	62	1.37	2.96	4.53	6.19	7.76	8.11
	63	2.05	3.49	5.05	6.52	7.79	8.45

Table B5
Fresh Structural Concrete Test Results

Mixture	Batch No.	Slump mm (in.)	Unit Weight kg/m^3 (lb/ft^3)	Air Content percent	Bleed percent	Underwater Flow mm (in.)
PUMP-1	1	100 (4)	2,326 (145.2)	5.0	2.2	380 (15)
	2	110 (4-1/4)	2,307 (144.0)	6.2	2.1	375 (14-3/4)
PUMP-11	1	100 (4)	2,316 (144.6)	5.6	2.0	380 (15)
	2	110 (4-1/2)	2,303 (143.8)	5.6	2.4	365 (14-1/2)
PUMP-2	1	160 (6-1/4)	2,323 (145.0)	5.0	4.0	385 (15-1/4)
	2	140 (5-1/2)	2,281 (142.4)	6.5	2.0	425 (16-3/4)
PUMP-21	1	100 (4)	2,275 (142.0)	6.2	1.9	405 (16)
	2	100 (4)	2,281 (142.4)	5.8	2.1	400 (15-3/4)
PUMP-3	1	140 (5-1/2)	2,294 (143.2)	6.5	2.4	405 (16)
	2	120 (4-3/4)	2,319 (144.8)	5.4	2.8	355 (14)

Table B6
Structural Concrete Compressive Strength Test Results

Mixture	Batch No.	Compresive Strength, MPa (psi)	
		7-day	28-day
PUMP-1	1	19.7 (2,850), 21.2 (3,080), 21.4 (3,100)	30.3 (4,390), 29.8 (4,320), 30.5 (4,420)
	2	20.8 (3,010), 21.0 (3,040), 19.7 (2,850)	28.9 (4,190), 27.7 (4,010), 29.4 (4,260)
PUMP-11	1	18.8 (2,720), 18.6 (2,690), 19.0 (2,760)	25.6 (3,710), 26.3 (3,820), 25.4 (3,680)
	2	18.7 (2,710), 18.3 (2,650), 18.1 (2,620)	25.6 (3,710), 24.8 (3,590), 27.1 (3,930)
PUMP-2	1	18.3 (2,650), 18.8 (2,720), 18.7 (2,710)	26.0 (3,770), 27.4 (3,980), 24.3 (3,520)
	2	17.9 (2,600), 18.3 (2,650), 18.2 (2,640)	27.3 (3,960), 27.0 (3,910), 27.6 (4,000)
PUMP-21	1	18.6 (2,690), 19.8 (2,870), 19.5 (2,830)	27.7 (4,010), 28.2 (4,090), 28.2 (3,890)
	2	20.3 (2,950), 18.3 (2,650), 20.5 (2,970)	28.5 (4,140), 28.7 (4,160), 28.5 (4,140)
PUMP-3	1	18.2 (2,640), 18.3 (2,650), 18.6 (2,690)	26.6 (3,860), 25.9 (3,750), 27.2 (3,940)
	2	19.2 (2,790), 20.3 (2,940), 19.2 (2,780)	28.3 (4,100), 28.7 (4,160), 27.8 (4,030)

Appendix C
Coarseness Factor Charts — SeeMIX Laboratory Evaluation

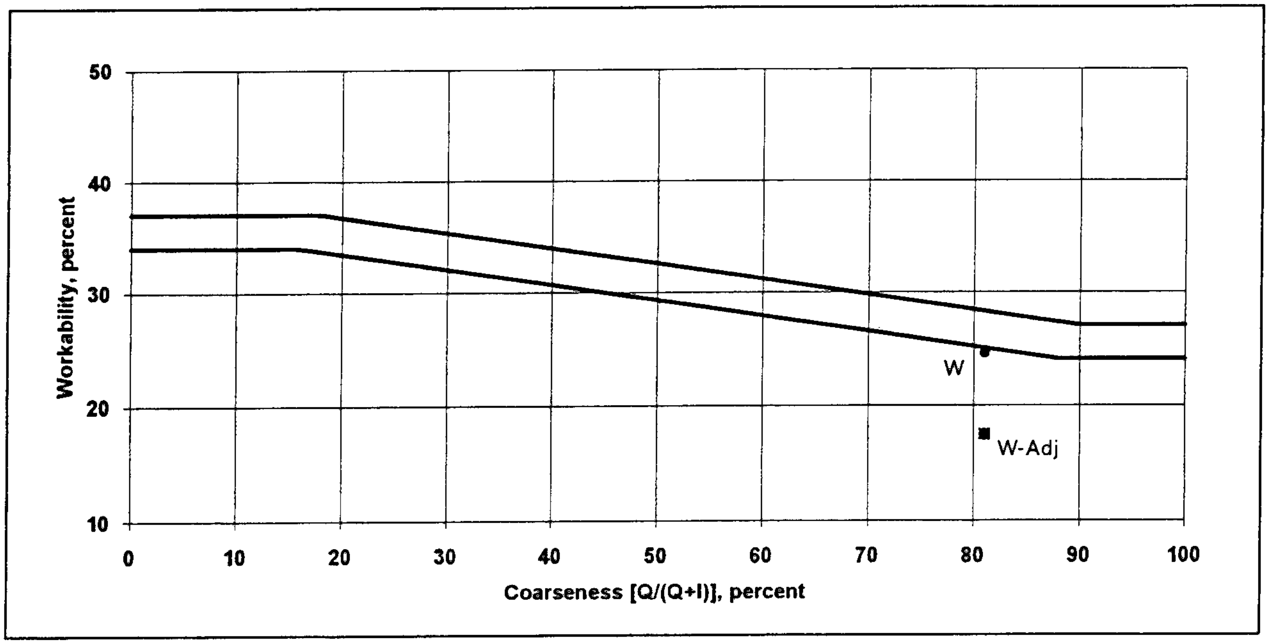


Figure C1. Coarseness Factor Chart for mixture MASS-1

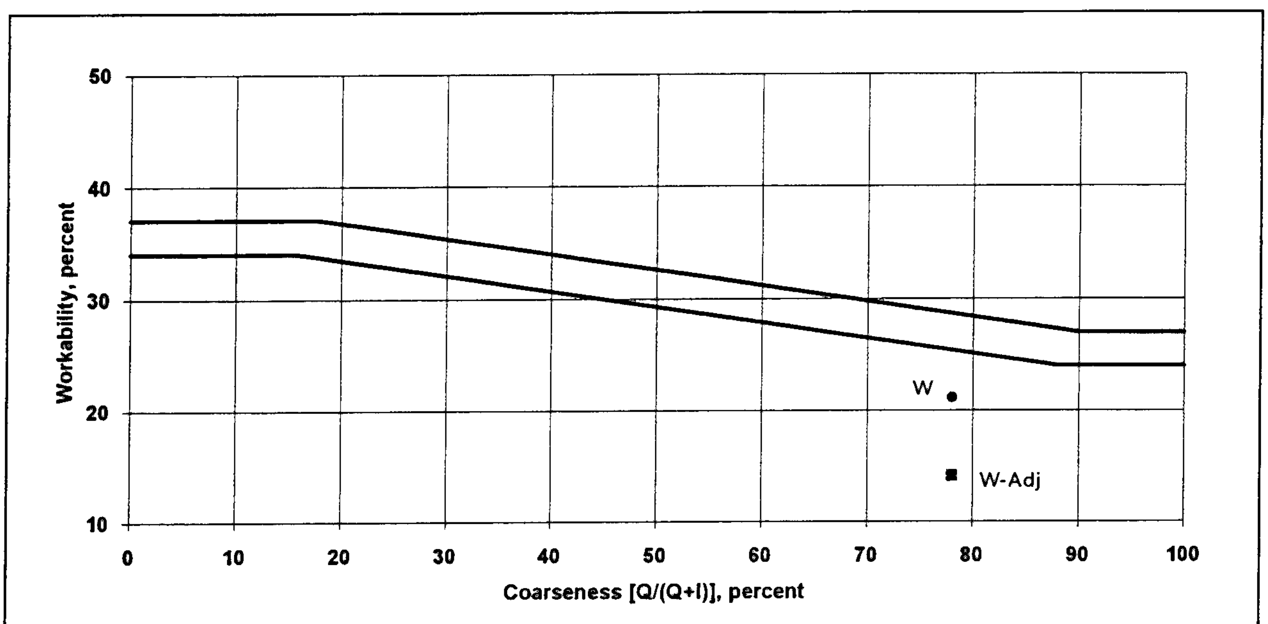


Figure C2. Coarseness Factor Chart for mixture MASS-2

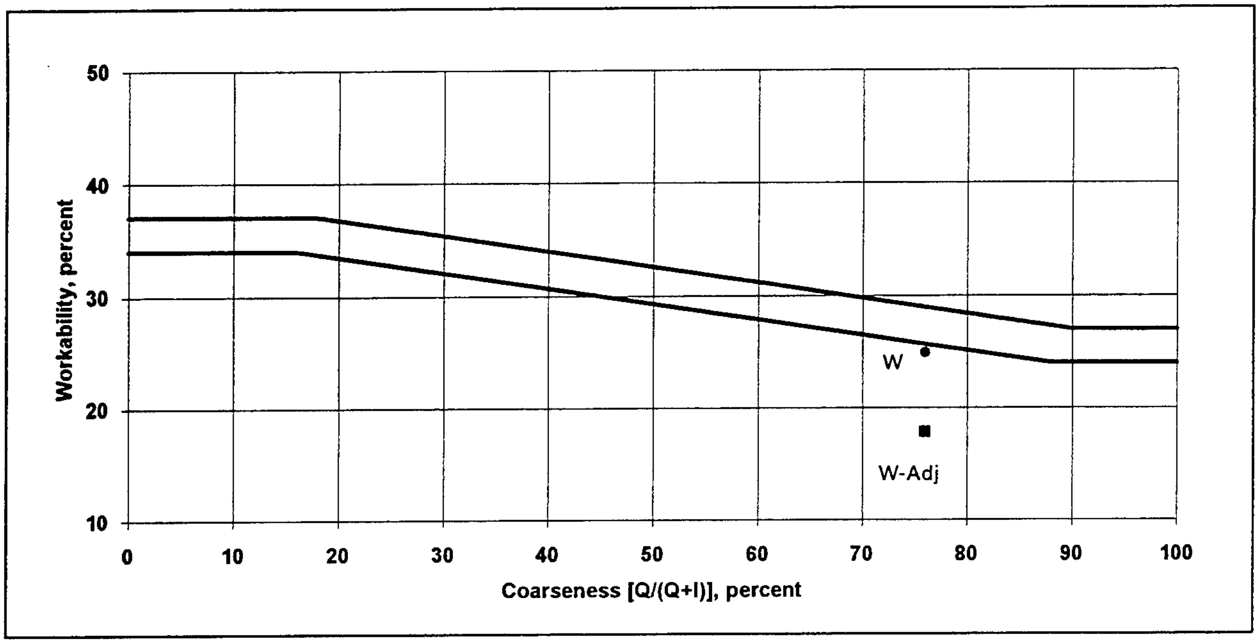


Figure C3. Coarseness Factor Chart for mixture MASS-3

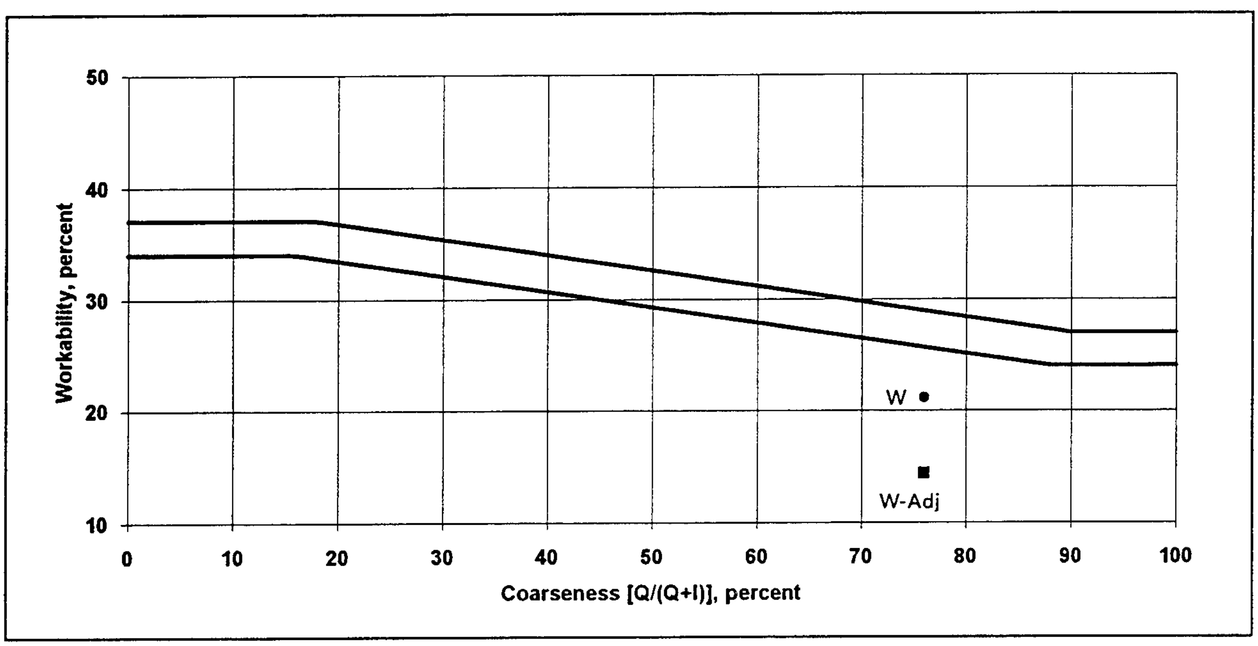


Figure C4. Coarseness Factor Chart for mixture MASS-21

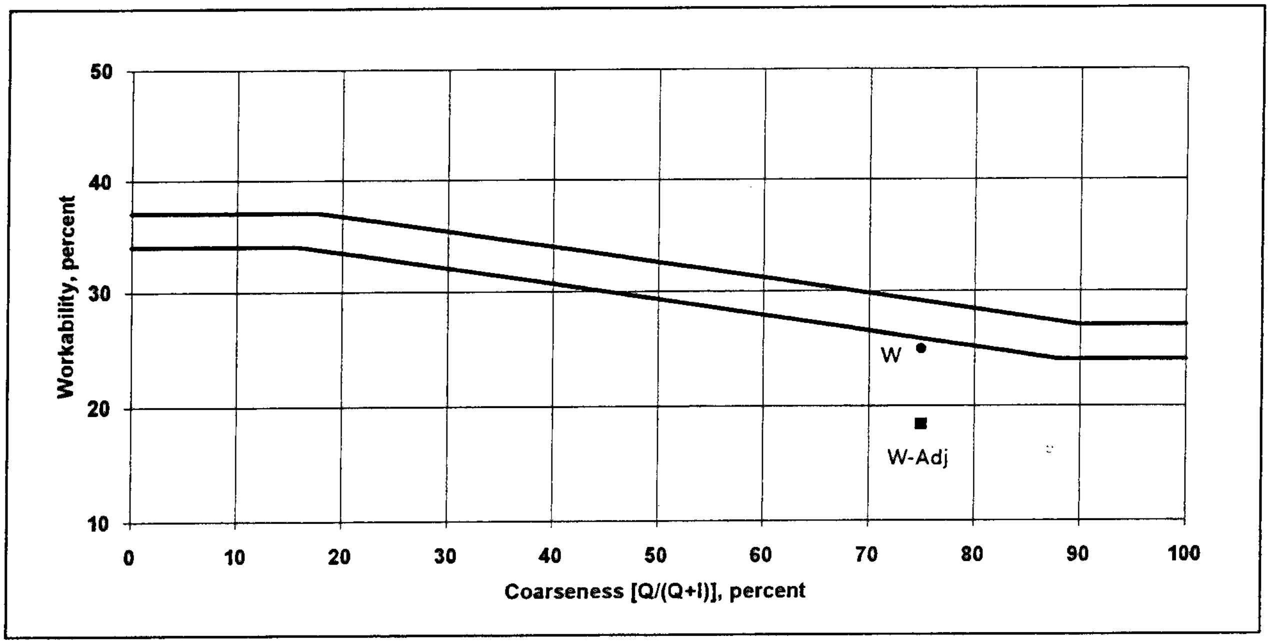


Figure C5. Coarseness Factor Chart for mixture MASS-31

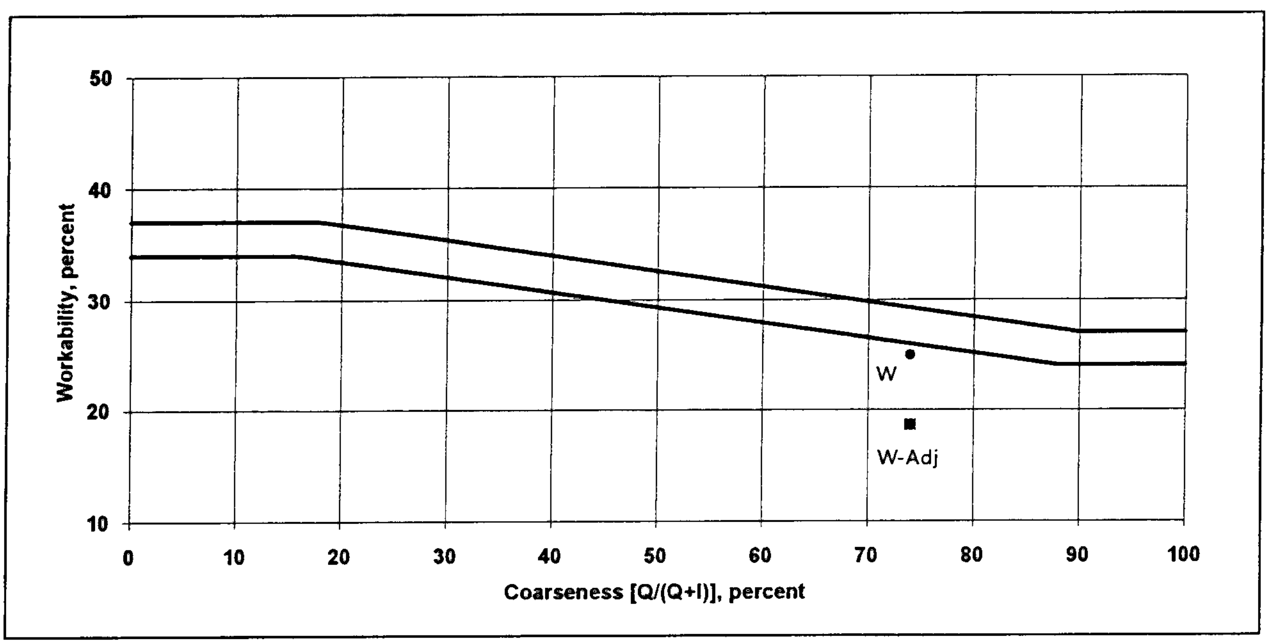


Figure C6. Coarseness Factor Chart for mixture MASS-32

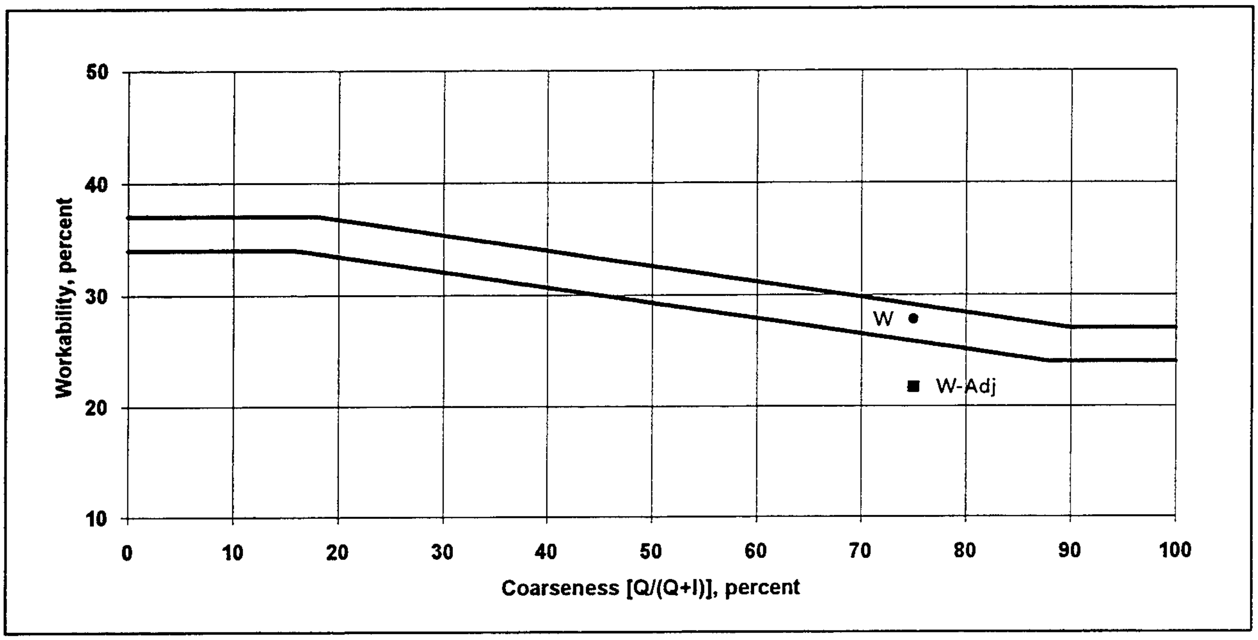
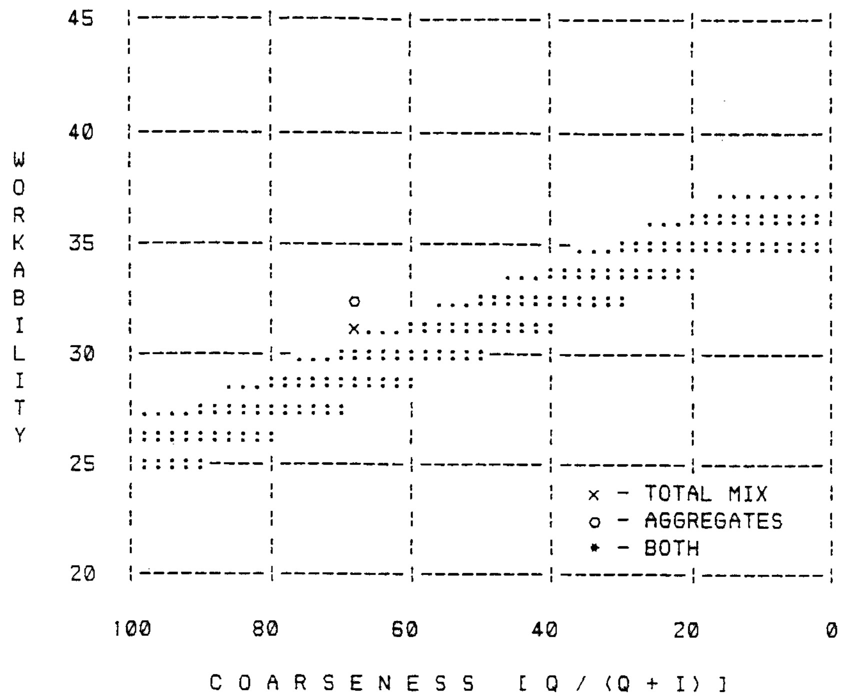


Figure C7. Coarseness Factor Chart for mixture MASS-4

Mix: PAVE

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	67.6
WORKABILITY	32.9
W - ADJUST	31.2
PERCENT MORTAR	51.7
TOTAL FINENESS MODULUS	5.48



MATERIALS CHARACTERISTICS

	STONE 1	STONE 2	SAND
DENSITY, SP G	2.74	2.77	2.59
% PASSING 3/8 " SIEVE	3.0	48.0	100.0
% PASSING # 8 SIEVE	-	2.0	79.0
FINENESS MODULUS	7.92	6.40	2.95
PERCENT OF AGGREGATE	32.8	26.2	41.0

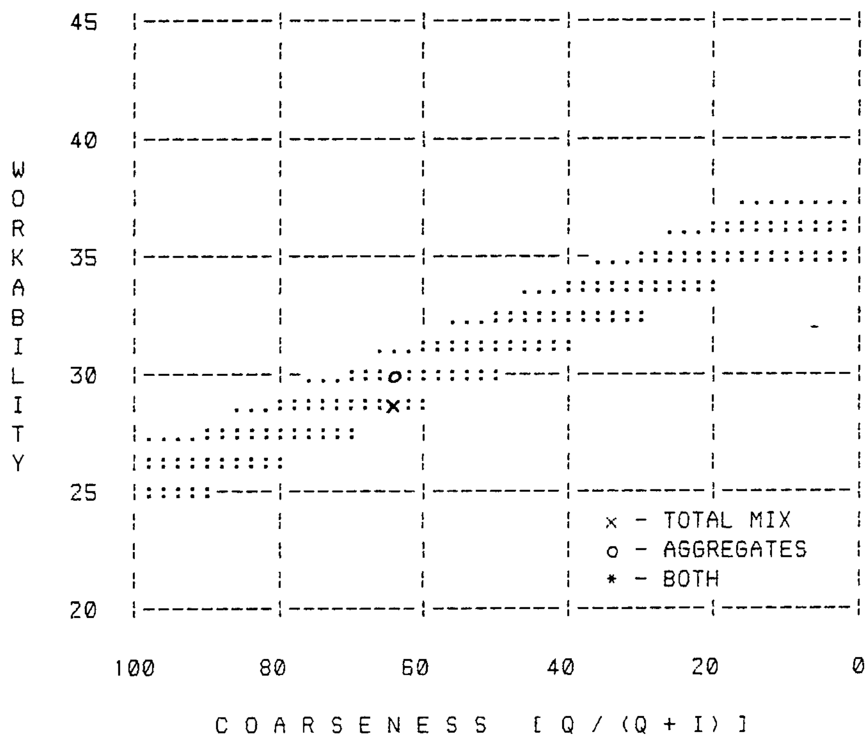
ANY SECTION -- WET / FREEZING

Figure C8. Coarseness Factor Chart for mixture PAVE-1

PSI: 5000 PSI   Mix: PAVE   04/24/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	63.5
WORKABILITY	30.0
W - ADJUST	28.3
PERCENT MORTAR	49.6
TOTAL FINENESS MODULUS	5.52



MATERIALS CHARACTERISTICS

	STONE 1	STONE 2	STONE 3	STONE 4	SAND
DENSITY, SP G	2.74	2.77	2.74	2.74	2.59
% PASSING 3/8 " SIEVE	3.0	48.0	-	-	100.0
% PASSING # 8 SIEVE	-	2.0	-	-	79.0
FINENESS MODULUS	7.92	6.40	8.00	7.00	2.95
PERCENT OF AGGREGATE	22.7	37.2	3.2	-	37.0

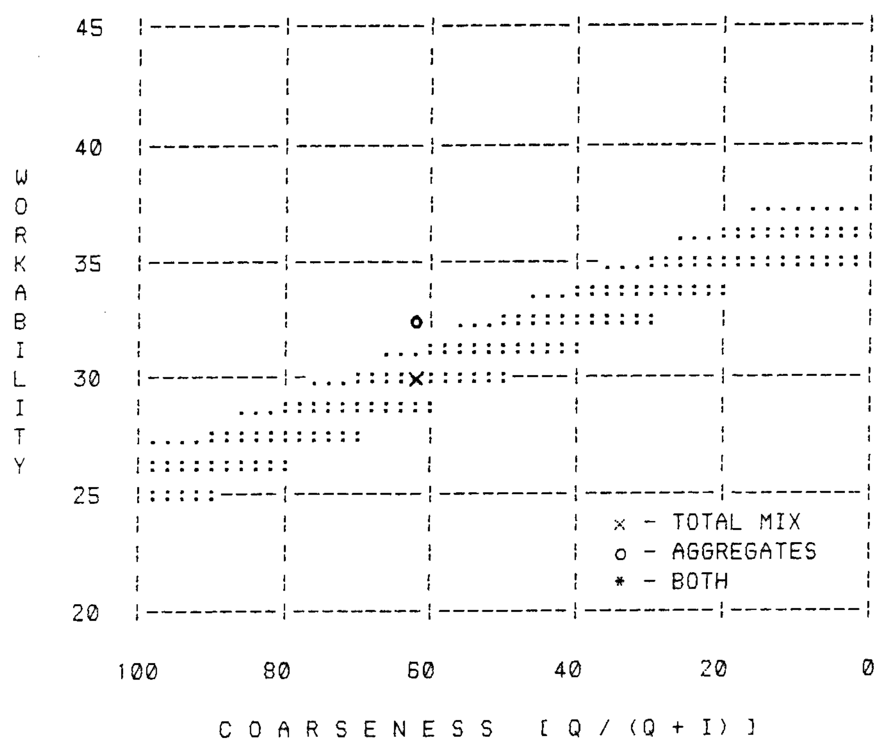
ANY SECTION -- WET / FREEZING

Figure C9. Coarseness Factor Chart for mixture PAVE-2

PSI: 5000 PSI	Mix: PAVE	04/24/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	62.7
WORKABILITY	32.0
W - ADJUST	30.3
PERCENT MORTAR	51.0
TOTAL FINENESS MODULUS	5.41



MATERIALS CHARACTERISTICS

	STONE 1	STONE 2	STONE 3	STONE 4	SAND
DENSITY, SP G	2.74	2.77	2.74	2.74	2.59
% PASSING 3/8 " SIEVE	3.0	48.0	-	-	100.0
% PASSING # 8 SIEVE	-	2.0	-	-	79.0
FINENESS MODULUS	7.92	6.40	8.00	7.00	2.95
PERCENT OF AGGREGATE	21.8	35.7	3.0	-	39.6

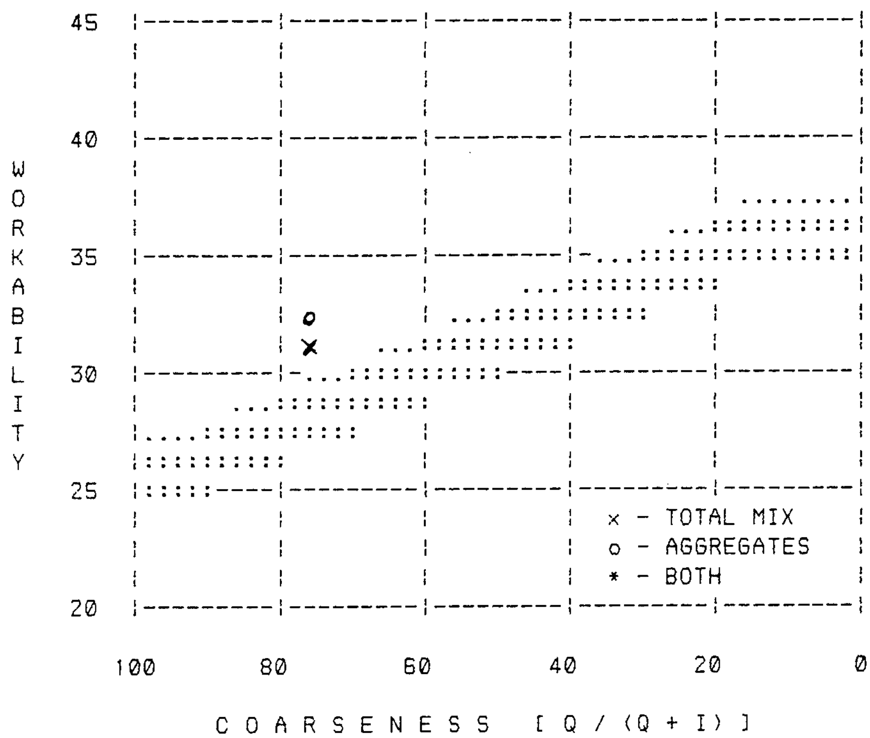
ANY SECTION -- WET / FREEZING

Figure C10. Coarseness Factor Chart for mixture PAVE-3

PSI: 5000 PSI Mix: PAVE 04/24/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	76.8
WORKABILITY	32.4
W - ADJUST	30.7
PERCENT MORTAR	51.3
TOTAL FINENESS MODULUS	5.64



MATERIALS CHARACTERISTICS

	STONE	SAND
DENSITY, SP G	2.75	2.59
% PASSING 3/8 " SIEVE	12.0	100.0
% PASSING # 8 SIEVE	-	79.0
FINENESS MODULUS	7.51	2.95
PERCENT OF AGGREGATE	59.0	41.0

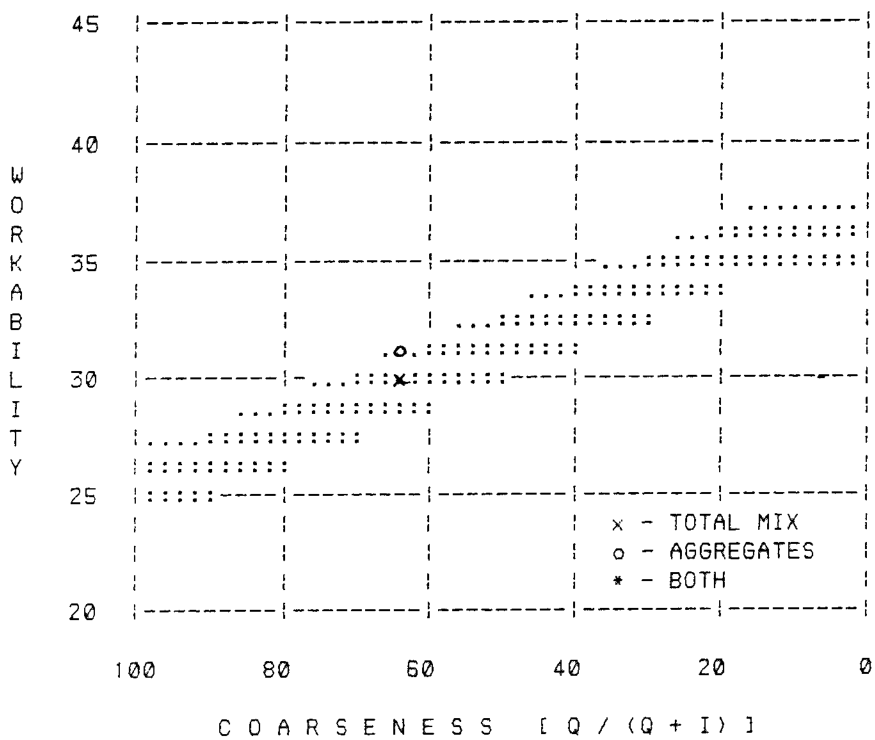
ANY SECTION -- WET / FREEZING

Figure C11. Coarseness Factor Chart for mixture PAVE-4

PSI: 5000 PSI | Mix: PAVE | 04/24/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	63.2
WORKABILITY	31.6
W - ADJUST	29.9
PERCENT MORTAR	50.7
TOTAL FINENESS MODULUS	5.39



MATERIALS CHARACTERISTICS

	STONE	SAND
DENSITY, SP G	2.75	2.59
% PASSING 3/8 " SIEVE	28.0	100.0
% PASSING # 8 SIEVE	-	79.0
FINENESS MODULUS	7.02	2.95
PERCENT OF AGGREGATE	60.0	40.0

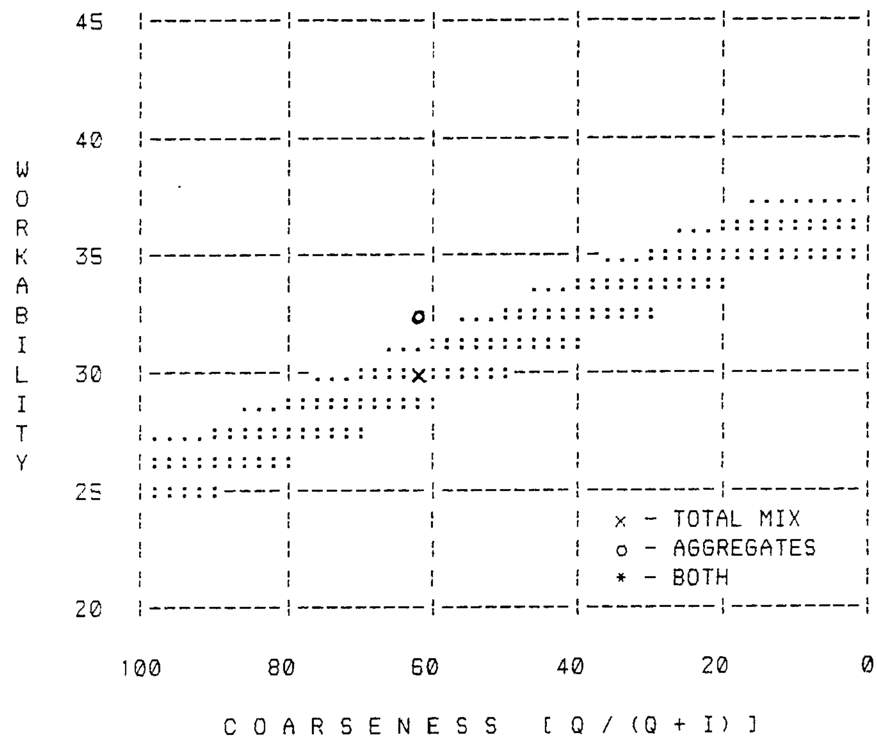
ANY SECTION -- WET / FREEZING

Figure C12. Coarseness Factor Chart for mixture PAVE-5

PSI: 5000 PSI Mix: PAVE 04/24/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	62.7
WORKABILITY	32.1
W - ADJUST	30.3
PERCENT MORTAR	51.0
TOTAL FINENESS MODULUS	5.41



MATERIALS CHARACTERISTICS

	STONE 1	STONE 2	STONE 3	STONE 4	SAND
DENSITY, SP G	2.74	2.77	2.74	2.74	2.59
% PASSING 3/8 " SIEVE	3.0	48.0	-	-	100.0
% PASSING # 8 SIEVE	-	2.0	-	-	79.0
FINENESS MODULUS	7.92	6.40	8.00	7.00	2.95
PERCENT OF AGGREGATE	21.7	35.5	3.0	-	39.8

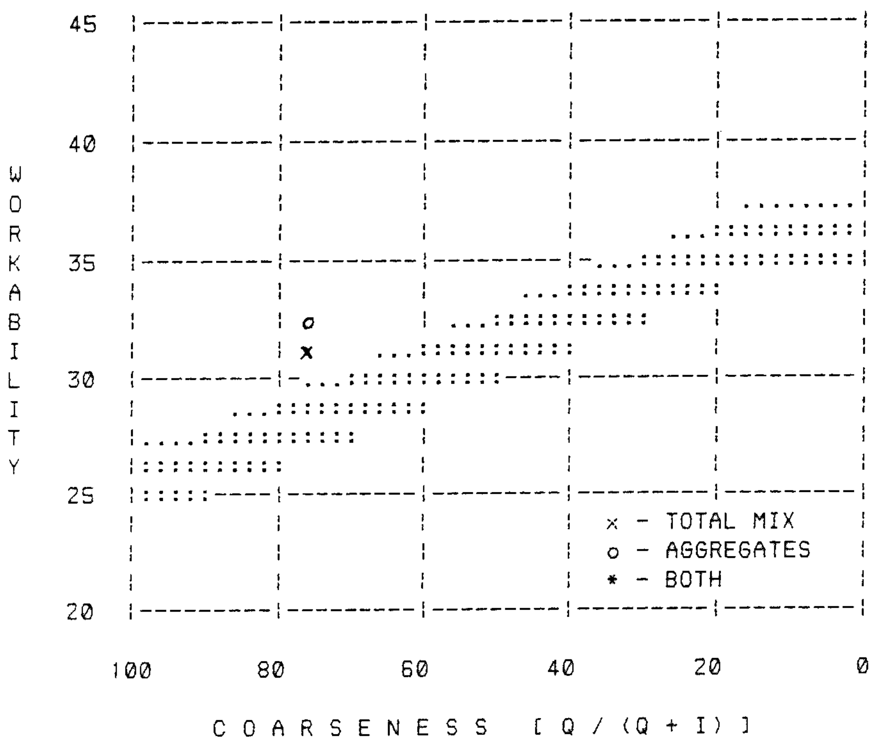
ANY SECTION -- WET / FREEZING

Figure C13. Coarseness Factor Chart for mixture PAVE-31

PSI: 5000 PSI   Mix: PAVE   04/24/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	76.5
WORKABILITY	33.0
W - ADJUST	30.7
PERCENT MORTAR	51.1
TOTAL FINENESS MODULUS	5.60



MATERIALS CHARACTERISTICS

	STONE	SAND
DENSITY, SP G	2.75	2.59
% PASSING 3/8 " SIEVE	12.0	100.0
% PASSING # 8 SIEVE	-	79.0
FINENESS MODULUS	7.51	2.95
PERCENT OF AGGREGATE	58.2	41.8

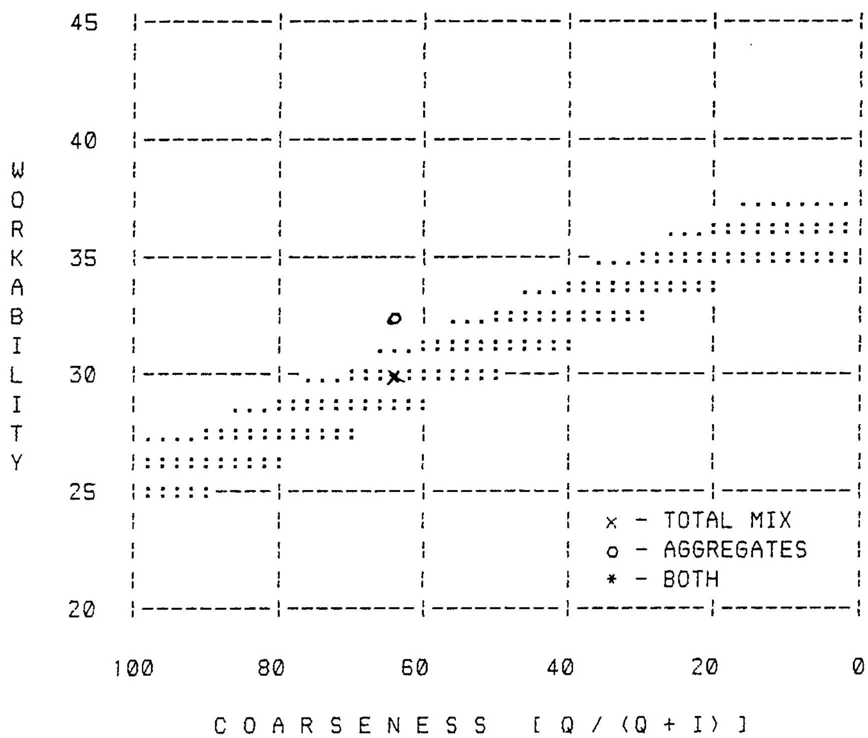
ANY SECTION -- WET / FREEZING

Figure C14. Coarseness Factor Chart for mixture PAVE-41

PSI: 5000 PSI | Mix: PAVE | 04/24/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	63.0
WORKABILITY	31.9
W - ADJUST	29.9
PERCENT MORTAR	50.6
TOTAL FINENESS MODULUS	5.38



MATERIALS CHARACTERISTICS

	STONE	SAND
DENSITY, SP G	2.75	2.59
% PASSING 3/8 " SIEVE	28.0	100.0
% PASSING # 8 SIEVE	-	79.0
FINENESS MODULUS	7.02	2.95
PERCENT OF AGGREGATE	59.6	40.4

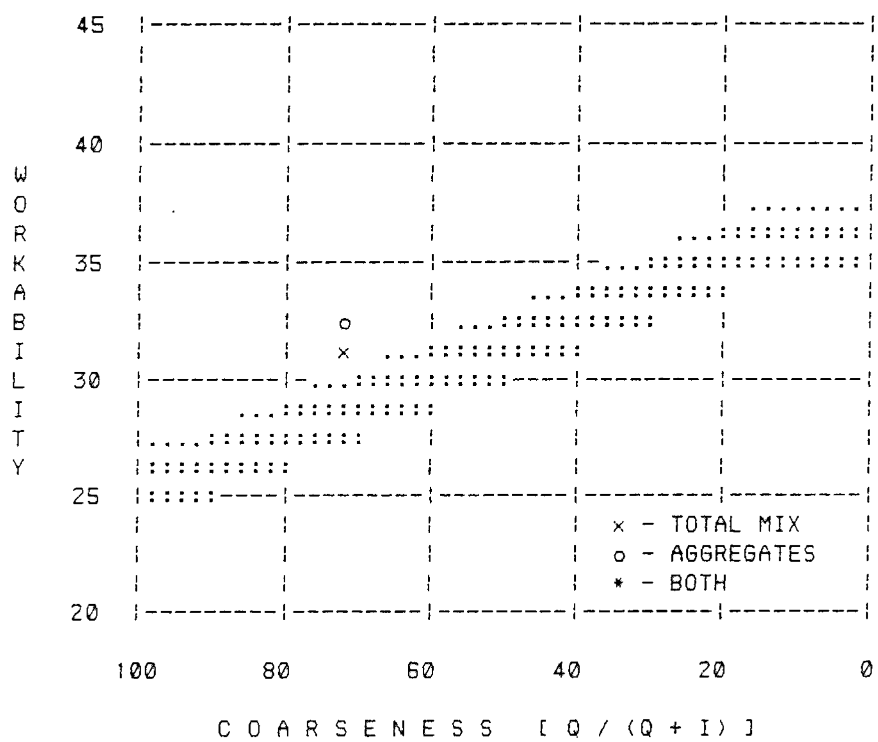
ANY SECTION -- WET / FREEZING

Figure C15. Coarseness Factor Chart for mixture PAVE-51

PSI: 4000 PSI	Mix: PAVE	04/24/91

MIX ANALYSIS

MIX VOLUME, CU FT	26.99
COARSENESS (Q / (Q + I))	71.4
WORKABILITY	32.8
W - ADJUST	31.1
PERCENT MORTAR	51.6
TOTAL FINENESS MODULUS	5.57



MATERIALS CHARACTERISTICS

	STONE	SAND
DENSITY, SP G	2.75	2.59
% PASSING 3/8 " SIEVE	20.0	100.0
% PASSING # 8 SIEVE	-	82.0
FINENESS MODULUS	7.27	3.03
PERCENT OF AGGREGATE	60.0	40.0

ANY SECTION -- SULFATES / SEA WATER

Figure C16. Coarseness Factor Chart for mixture PAVE-6

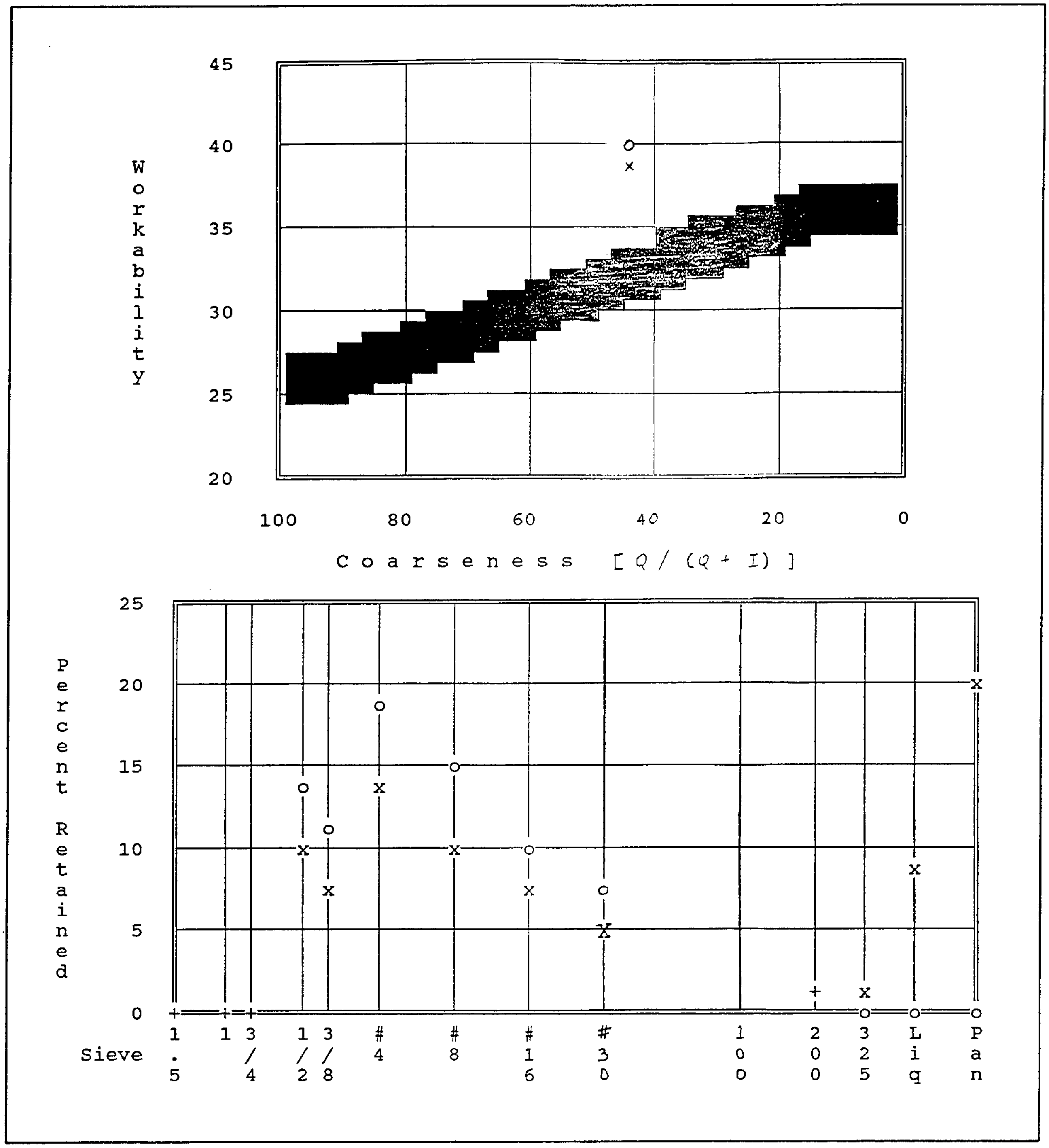
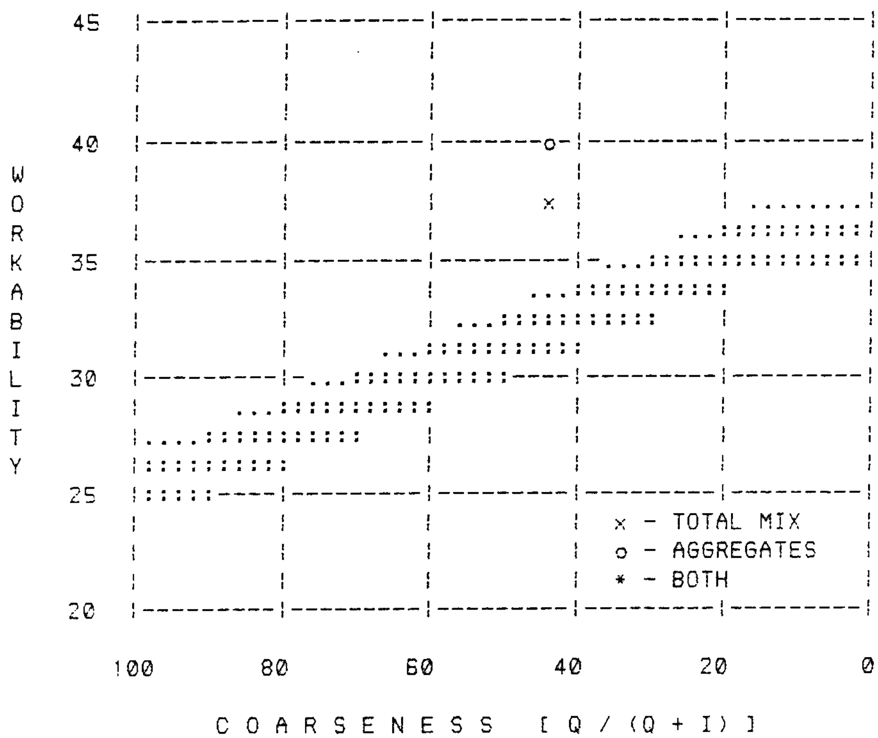


Figure C17. Coarseness Factor Chart for mixture PUMP-1

PSI: 4000 PSI Mix: PUMP 04/17/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	44.0
WORKABILITY	39.7
W - ADJUST	37.3
PERCENT MORTAR	58.0
TOTAL FINENESS MODULUS	4.71



MATERIALS CHARACTERISTICS

	STONE	SAND
DENSITY, SP G	2.77	2.59
% PASSING 3/8 " SIEVE	48.0	100.0
% PASSING # 8 SIEVE	2.0	79.0
FINENESS MODULUS	6.40	2.95
PERCENT OF AGGREGATE	51.0	49.0

MINERAL ADMIXTURE DENSITY, SP G 2.30

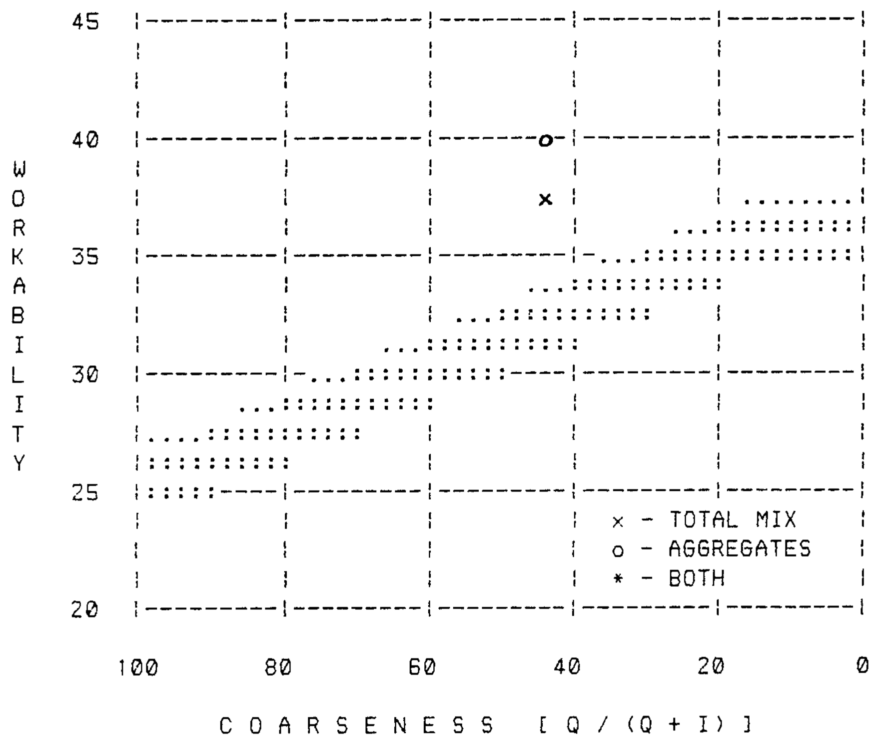
ANY SECTION -- WET / FREEZING

Figure C18. Coarseness Factor Chart for mixture PUMP-2

PSI: 4000 PSI　　Mix: PUMP　　04/25/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	44.0
WORKABILITY	39.7
W - ADJUST	36.9
PERCENT MORTAR	57.5
TOTAL FINENESS MODULUS	4.71



MATERIALS CHARACTERISTICS

	STONE	SAND
DENSITY, SP G	2.77	2.59
% PASSING 3/8 " SIEVE	48.0	100.0
% PASSING # 8 SIEVE	2.0	79.0
FINENESS MODULUS	6.40	2.95
PERCENT OF AGGREGATE	51.0	49.0

MINERAL ADMIXTURE DENSITY, SP G　　2.30

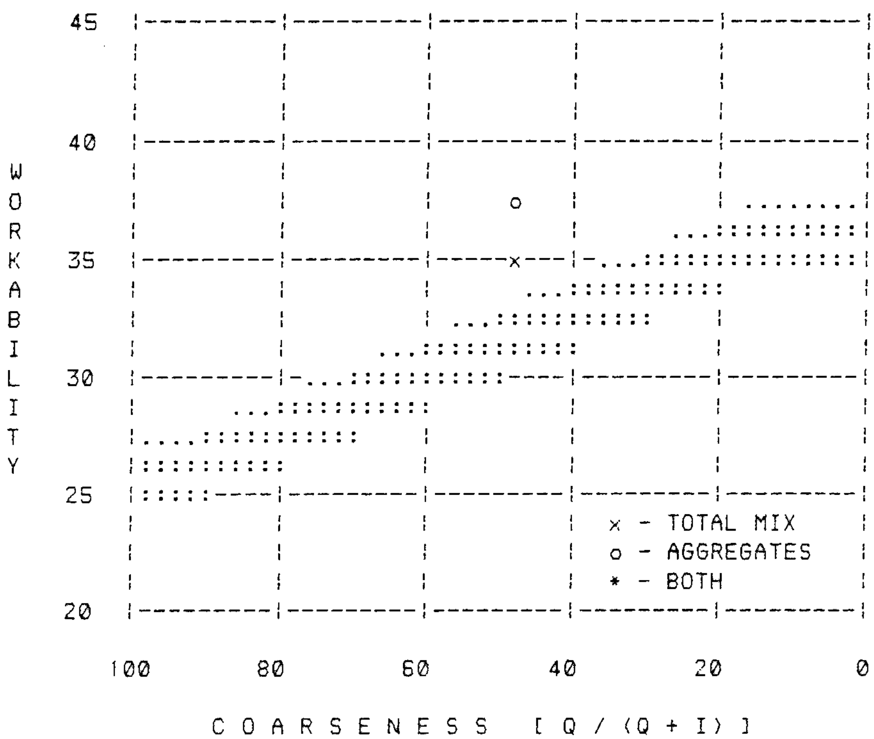
ANY SECTION -- WET / FREEZING

Figure C19. Coarseness Factor Chart for mixture PUMP-21

PSI: 4000 PSI | Mix: PUMP | 04/18/91

MIX ANALYSIS

MIX VOLUME, CU FT	27.00
COARSENESS (Q / (Q + I))	47.3
WORKABILITY	37.3
W - ADJUST	34.9
PERCENT MORTAR	56.3
TOTAL FINENESS MODULUS	4.78



MATERIALS CHARACTERISTICS

	STONE	SAND 1	SAND 2
DENSITY, SP G	2.77	2.59	2.63
% PASSING 3/8 " SIEVE	48.0	100.0	100.0
% PASSING # 8 SIEVE	2.0	79.0	100.0
FINENESS MODULUS	6.40	2.95	1.67
PERCENT OF AGGREGATE	57.0	32.2	10.7

MINERAL ADMIXTURE DENSITY, SP G 2.30

ANY SECTION -- WET / FREEZING

Figure C20. Coarseness Factor Chart for mixture PUMP-3

Appendix D
Combined Aggregate Grading and Aggregate Particle for Distribution for Paving and Pump Mixtures — SeeMIX Laboratory Evaluation

FULL GRADATION ANALYSIS

SIEVE	STONE 1	STONE 2	SAND	PASTE	TOTAL	AGGR
1-1/2 "	96.0				99.1	98.7
1 "	29.0	100.0			83.2	76.7
3/4 "	7.0	99.0			77.8	69.2
1/2 "	3.0	71.0			71.6	60.6
3/8 "	3.0	48.0	100.0		67.3	54.6
# 4	2.0	11.0	99.0		59.8	44.1
# 8	-	2.0	79.0		51.7	32.9
# 16	-	-	60.0		45.7	24.6
# 30	-	-	46.0		41.6	18.9
# 50	-	-	18.0		33.3	7.4
# 100	-	-	3.0		28.9	1.2
# 200	-	-	-	100.0	28.0	-
# 325	-	-	-	94.9	26.6	-
Liquid	-	-	-	66.3	18.5	-

GRADATION CHART

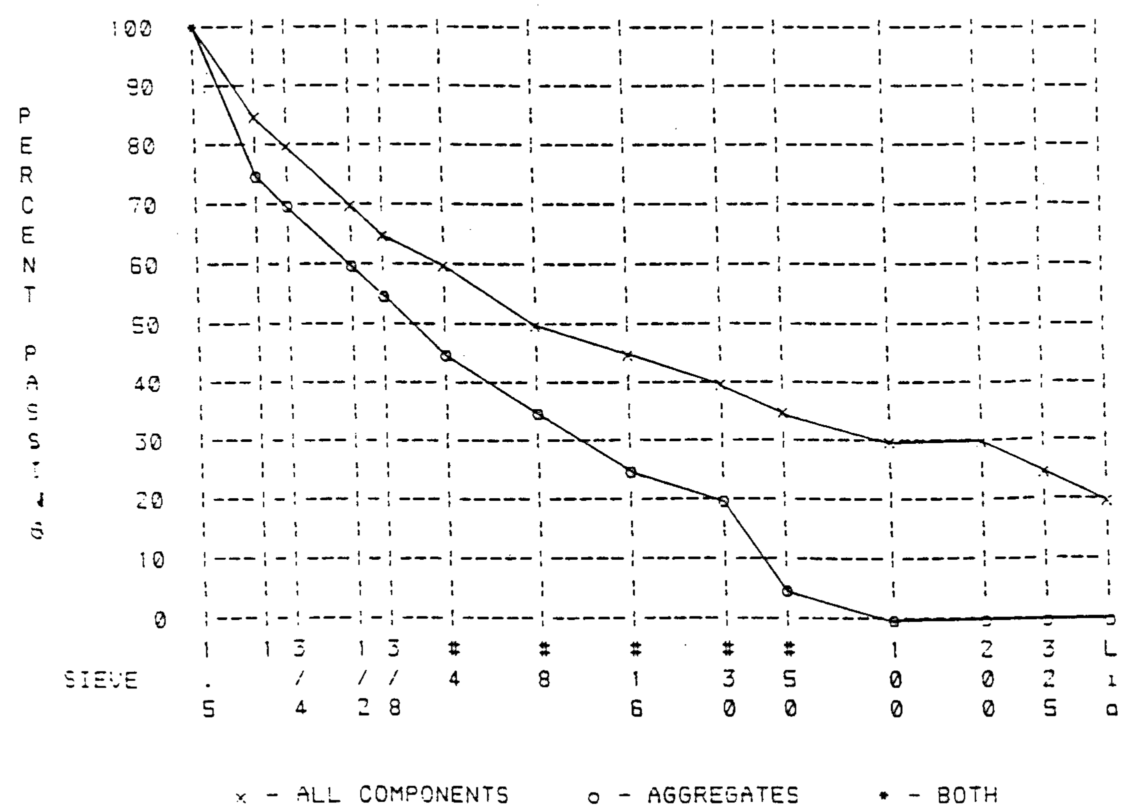


Figure D1. Combined aggregate grading for mixture PAVE-1

PSI: 5000 PSI Mix: PAVE 04/24/91

FULL GRADATION ANALYSIS

SIEVE	STONE 1	STONE 2	STONE 3	STONE 4	SAND	PASTE	TOTAL	AGGR
1-1/2 "	96.0						99.3	99.1
1 "	29.0	100.0	100.0				88.4	83.9
3/4 "	7.0	99.0	-	100.0			82.3	75.4
1/2 "	3.0	71.0	-	-			74.1	64.1
3/8 "	3.0	48.0	-	-	100.0		68.0	55.5
# 4	2.0	11.0	-	-	99.0		57.6	41.2
# 8	-	2.0	-	-	79.0		49.6	30.0
# 16	-	-	-	-	60.0		44.0	22.2
# 30	-	-	-	-	46.0		40.2	17.0
# 50	-	-	-	-	18.0		32.8	6.7
# 100	-	-	-	-	3.0		28.8	1.1
# 200	-	-	-	-	-	100.0	28.0	-
# 325	-	-	-	-	-	94.9	26.6	-
Liquid	-	-	-	-	-	66.3	18.6	-

GRADATION CHART

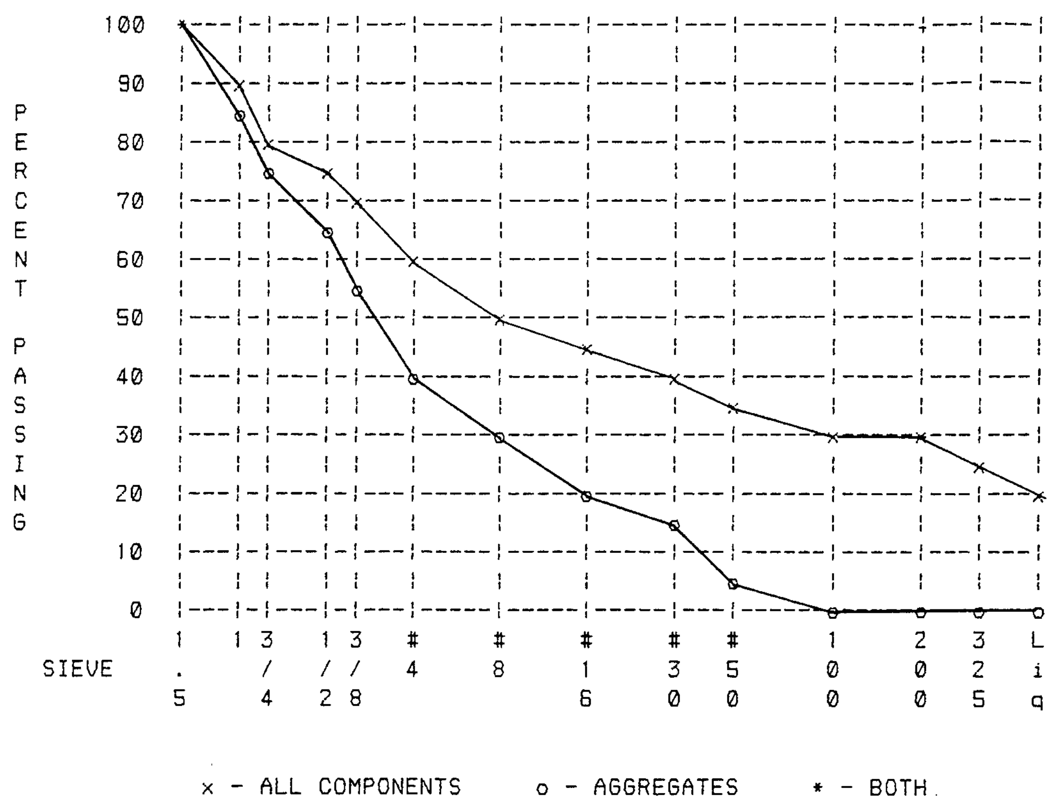


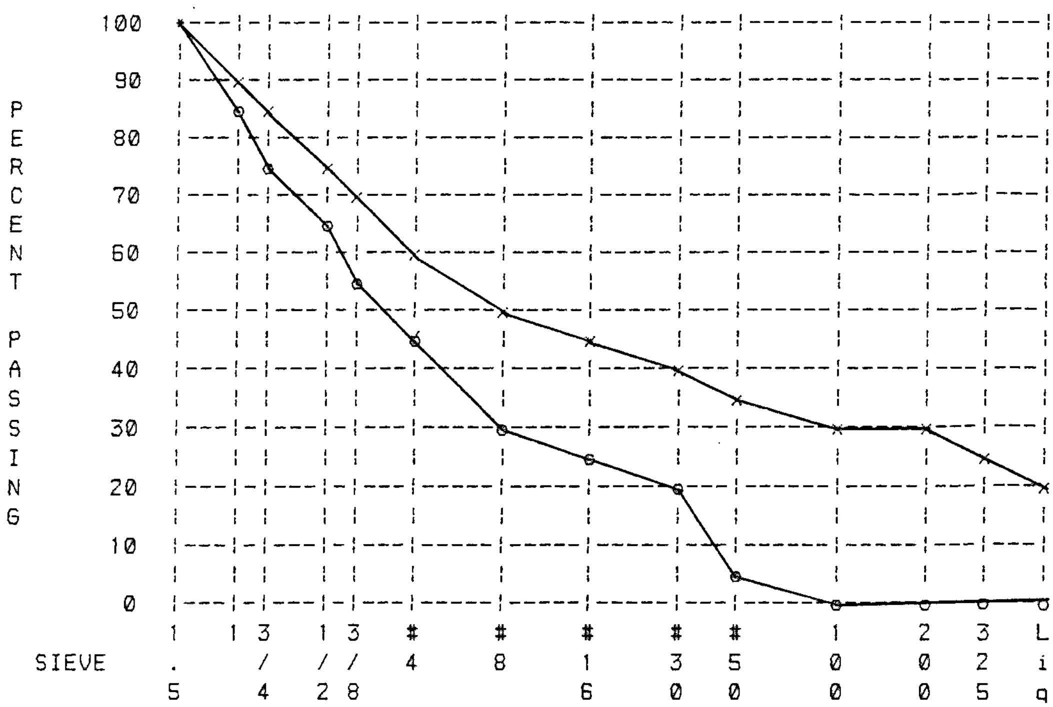
Figure D2. Combined aggregate grading for mixture PAVE-2

PSI: 5000 PSI Mix: PAVE 04/24/91

FULL GRADATION ANALYSIS

SIEVE	STONE 1	STONE 2	STONE 3	STONE 4	SAND	PASTE	TOTAL	AGGR
1-1/2 "	96.0						99.4	99.1
1 "	29.0	100.0	100.0				88.9	84.6
3/4 "	7.0	99.0	-	100.0			83.0	76.4
1/2 "	3.0	71.0	-	-			75.2	65.5
3/8 "	3.0	48.0	-	-	100.0		69.3	57.3
# 4	2.0	11.0	-	-	99.0		59.3	43.5
# 8	-	2.0	-	-	79.0		51.0	32.0
# 16	-	-	-	-	60.0		45.1	23.7
# 30	-	-	-	-	46.0		41.1	18.2
# 50	-	-	-	-	18.0		33.1	7.1
# 100	-	-	-	-	3.0		28.8	1.2
# 200	-	-	-	-	-	100.0	28.0	-
# 325	-	-	-	-	-	94.9	26.6	-
Liquid	-	-	-	-	-	66.3	18.6	-

GRADATION CHART



x - ALL COMPONENTS o - AGGREGATES * - BOTH

Figure D3. Combined aggregate grading for mixture PAVE-3

PSI: 5000 PSI Mix: PAVE 04/24/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	98.0			99.2	98.8
1 "	62.0			83.9	77.6
3/4 "	37.0			73.2	62.8
1/2 "	22.0			66.9	54.0
3/8 "	12.0	100.0		62.6	48.1
# 4	2.0	99.0		58.1	41.8
# 8	-	79.0		51.3	32.4
# 16	-	60.0		45.7	24.6
# 30	-	46.0		41.6	18.9
# 50	-	18.0		33.3	7.4
# 100	-	3.0		28.9	1.2
# 200	-	-	100.0	28.0	-
# 325	-	-	94.9	26.6	-
Liquid	-	-	66.3	18.6	-

GRADATION CHART

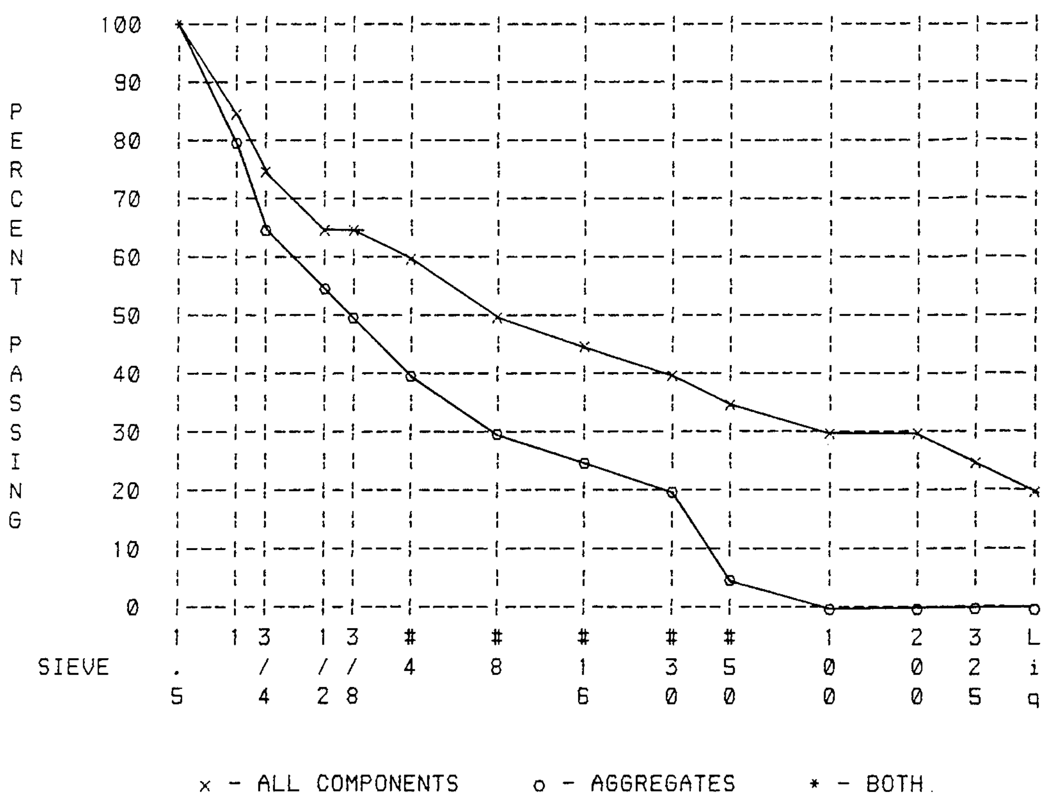


Figure D4. Combined aggregate grading for mixture PAVE-4

PSI: 5000 PSI　　Mix: PAVE　　04/24/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	99.0			99.6	99.4
1 "	80.0			91.4	88.0
3/4 "	68.0			86.2	80.8
1/2 "	44.0			75.8	66.4
3/8 "	28.0	100.0		68.9	56.8
# 4	3.0	99.0		57.8	41.4
# 8	-	79.0		50.7	31.6
# 16	-	60.0		45.3	24.0
# 30	-	46.0		41.2	18.4
# 50	-	18.0		33.2	7.2
# 100	-	3.0		28.8	1.2
# 200	-	-	100.0	28.0	-
# 325	-	-	94.9	26.6	-
Liquid	-	-	66.3	18.6	-

GRADATION CHART

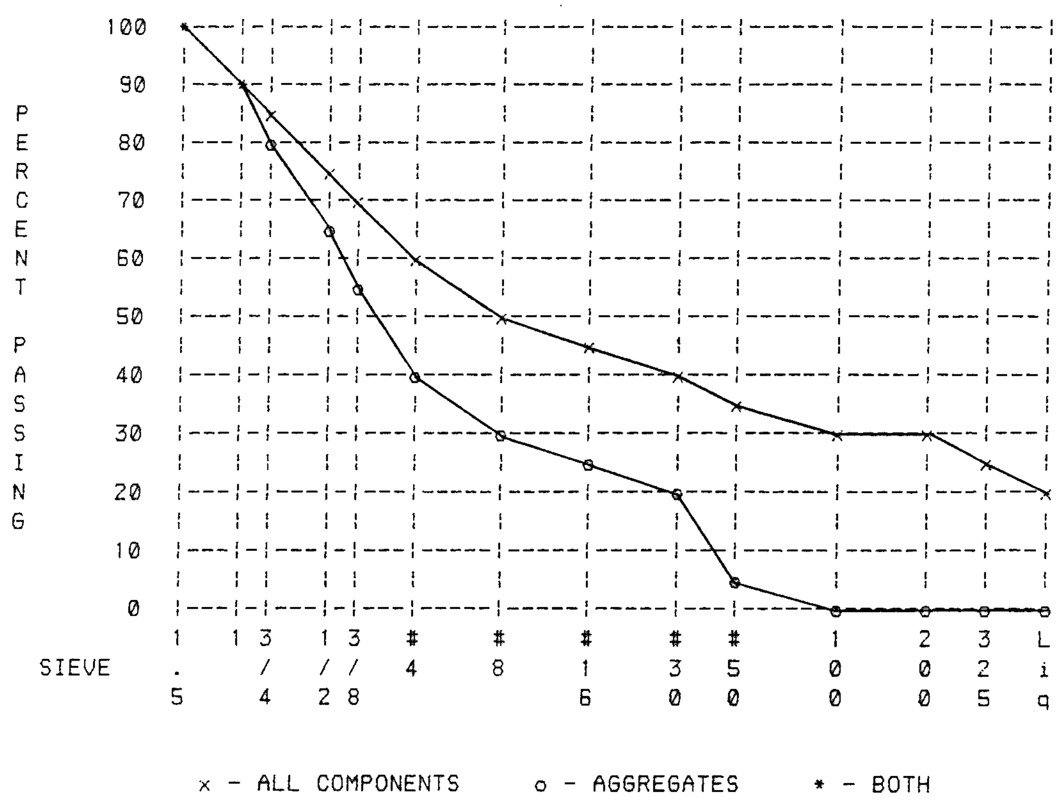


Figure D5. Combined aggregate grading for mixture PAVE-5

PSI: 5000 PSI Mix: PAVE 04/24/91

FULL GRADATION ANALYSIS

SIEVE	STONE 1	STONE 2	STONE 3	STONE 4	SAND	PASTE	TOTAL	AGGR
1-1/2 "	96.0						99.4	99.1
1 "	29.0	100.0	100.0				88.9	84.6
3/4 "	7.0	99.0	-	100.0			83.0	76.5
1/2 "	3.0	71.0	-	-			75.2	65.6
3/8 "	3.0	48.0	-	-	100.0		69.3	57.5
# 4	2.0	11.0	-	-	99.0		59.3	43.7
# 8	-	2.0	-	-	79.0		51.0	32.1
# 16	-	-	-	-	60.0		45.0	23.9
# 30	-	-	-	-	46.0		41.0	18.3
# 50	-	-	-	-	18.0		32.9	7.2
# 100	-	-	-	-	3.0		28.6	1.2
# 200	-	-	-	-	-	100.0	27.8	-
# 325	-	-	-	-	-	95.0	26.4	-
Liquid	-	-	-	-	-	66.4	18.4	-

GRADATION CHART

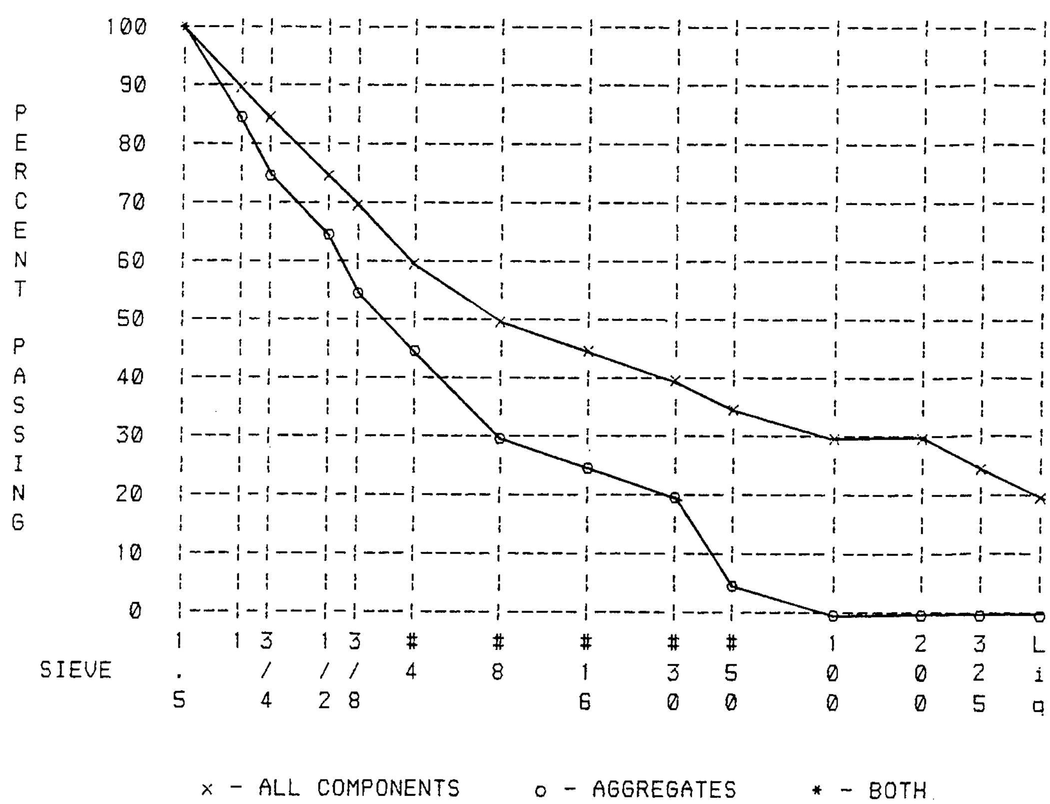


Figure D6. Combined aggregate grading for mixture PAVE-31

PSI: 5000 PSI Mix: PAVE 04/24/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	98.0			99.1	98.8
1 "	62.0			83.8	77.9
3/4 "	37.0			73.2	63.3
1/2 "	22.0			66.8	54.6
3/8 "	12.0	100.0		62.6	48.8
# 4	2.0	99.0		58.0	42.5
# 8	-	79.0		51.1	33.0
# 16	-	60.0		45.3	25.1
# 30	-	46.0		41.0	19.2
# 50	-	18.0		32.5	7.5
# 100	-	3.0		27.9	1.3
# 200	-	-	100.0	27.0	-
# 325	-	-	95.0	25.6	-
Liquid	-	-	66.6	18.0	-

GRADATION CHART

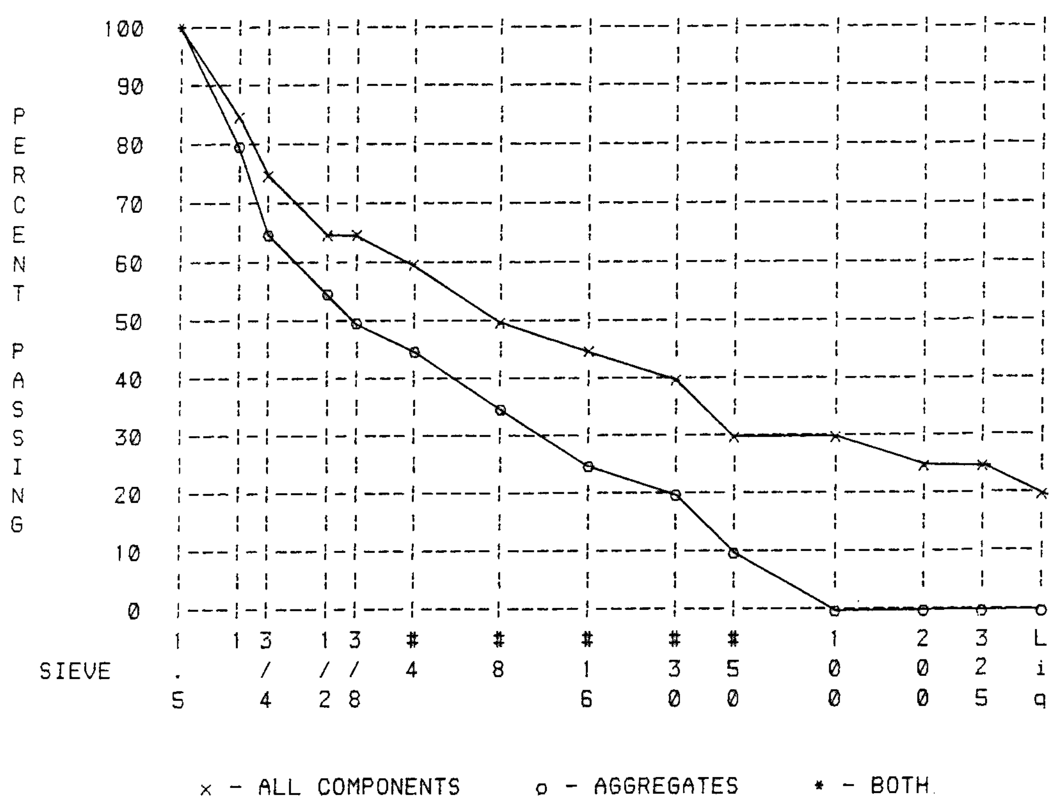


Figure D7. Combined aggregate grading for mixture PAVE-41

PSI: 5000 PSI   Mix: PAVE   04/24/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	99.0			99.6	99.4
1 "	80.0			91.4	88.1
3/4 "	68.0			86.2	80.9
1/2 "	44.0			75.8	66.6
3/8 "	28.0	100.0		68.9	57.1
# 4	3.0	99.0		57.8	41.8
# 8	-	79.0		50.6	31.9
# 16	-	60.0		45.0	24.2
# 30	-	46.0		40.9	18.6
# 50	-	18.0		32.7	7.3
# 100	-	3.0		28.3	1.2
# 200	-	-	100.0	27.5	-
# 325	-	-	95.0	26.1	-
Liquid	-	-	66.5	18.3	-

GRADATION CHART

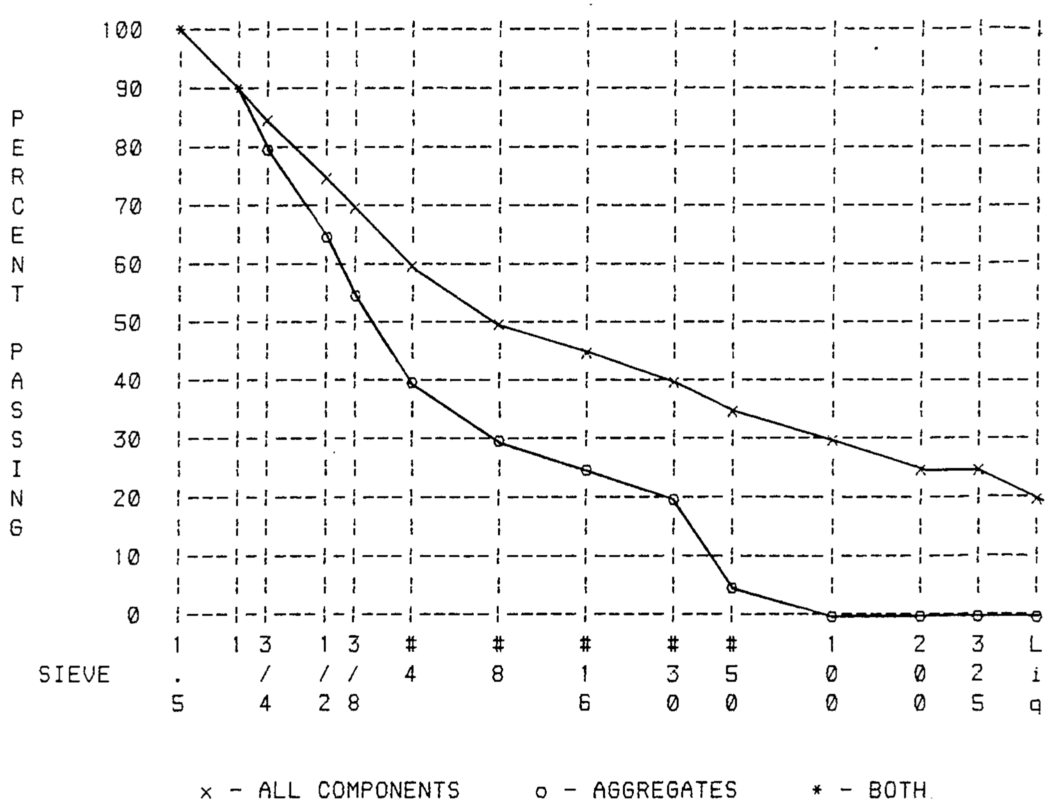


Figure D8. Combined aggregate grading for mixture PAVE-51

PSI: 4000 PSI Mix: PAVE 04/24/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	98.0			99.1	98.8
1 "	62.0			83.6	77.2
3/4 "	53.0			79.7	71.8
1/2 "	44.0			75.8	66.4
3/8 "	20.0	100.0		65.4	52.0
# 4	2.0	93.0		55.7	38.4
# 8	-	82.0		51.6	32.8
# 16	-	70.0		48.2	28.0
# 30	-	46.0		41.2	18.4
# 50	-	6.0		29.7	2.4
# 100	-	-		28.0	-
# 200	-	-	100.0	28.0	-
# 325	-	-	94.9	26.6	-
Liquid	-	-	66.3	18.6	-

GRADATION CHART

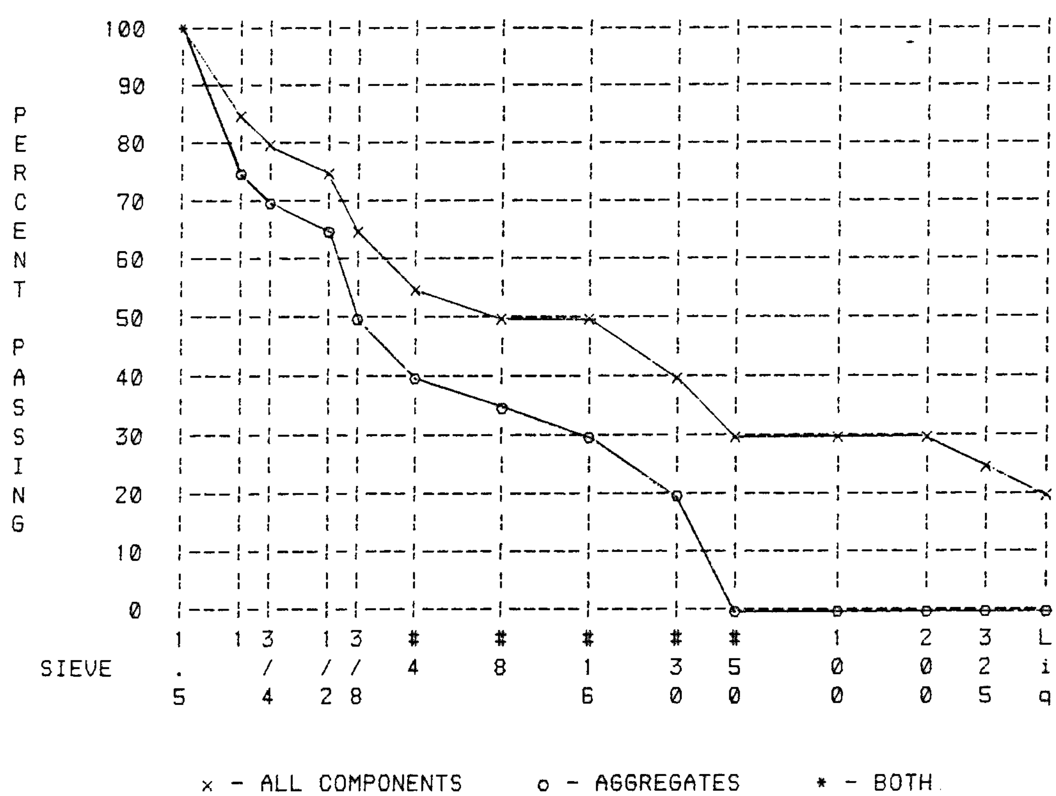


Figure D9. Combined aggregate grading for mixture PAVE-6

PSI: 5000 PSI　　Mix: PAVE　　04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE 1	STONE 2	SAND	PASTE	TOTAL	AGGR
1-1/2 "	96.0				0.9	1.3
1 "	29.0	100.0			15.8	22.0
3/4 "	7.0	99.0			5.4	7.5
1/2 "	3.0	71.0			6.2	8.6
3/8 "	3.0	48.0	100.0		4.3	6.0
# 4	2.0	11.0	99.0		7.5	10.4
# 8	-	2.0	79.0		8.1	11.2
# 16	-	-	60.0		6.0	8.3
# 30	-	-	46.0		4.1	5.7
# 50	-	-	18.0		8.3	11.5
# 100	-	-	3.0		4.4	6.2
# 200	-	-	-	100.0	0.9	1.2
# 325	-	-	-	94.9	1.4	-
Liquid	-	-	-	66.3	8.0	-

MATERIALS DISTRIBUTION CHART BY SIEVE

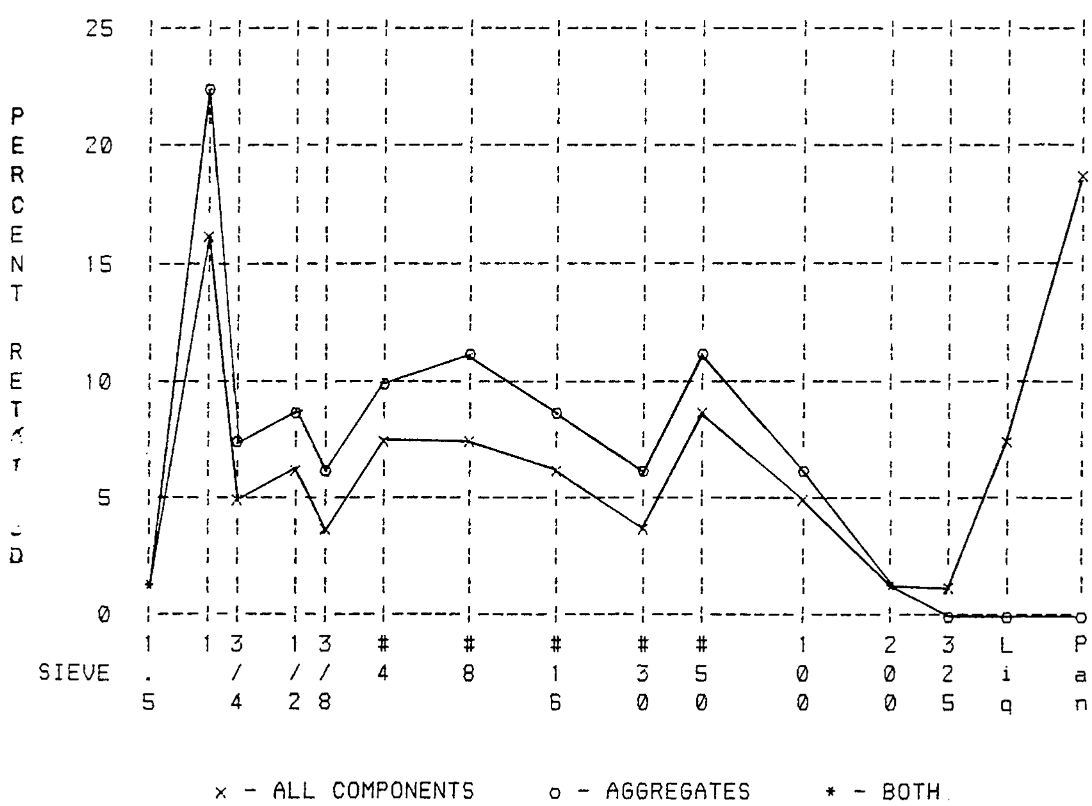


Figure D10. Aggregate particle distribution for mixture PAVE-1

PSI: 5000 PSI Mix: PAVE 04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE 1	STONE 2	STONE 3	STONE 4	SAND	PASTE	TOTAL	AGGR
1-1/2 "	96.0						0.7	0.9
1 "	29.0	100.0	100.0				10.9	15.2
3/4 "	7.0	99.0	-	100.0			6.1	8.5
1/2 "	3.0	71.0	-	-			8.1	11.3
3/8 "	3.0	48.0	-	-	100.0		6.2	8.5
# 4	2.0	11.0	-	-	99.0		10.3	14.3
# 8	-	2.0	-	-	79.0		8.1	11.2
# 16	-	-	-	-	60.0		5.6	7.8
# 30	-	-	-	-	46.0		3.7	5.2
# 50	-	-	-	-	18.0		7.5	10.4
# 100	-	-	-	-	3.0		4.0	5.6
# 200	-	-	-	-	-	100.0	0.8	1.1
# 325	-	-	-	-	-	94.9	1.4	-
Liquid	-	-	-	-	-	66.3	8.0	-

MATERIALS DISTRIBUTION CHART BY SIEVE

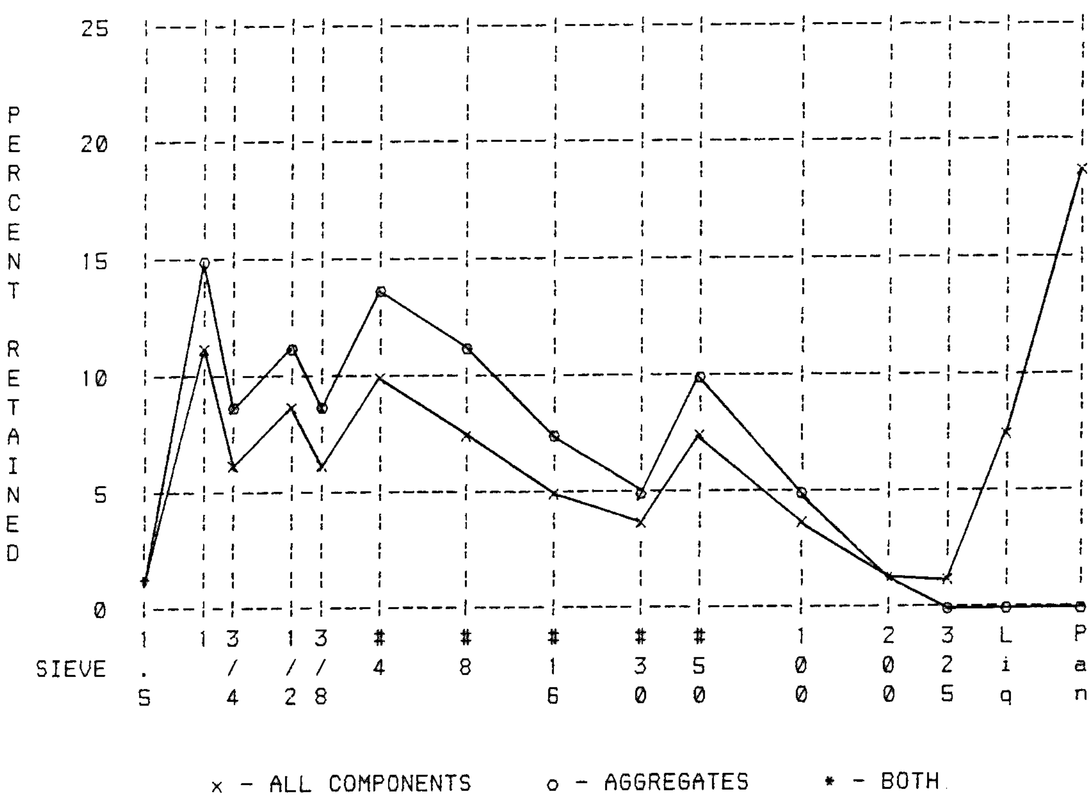


Figure D11. Aggregate particle distribution for mixture PAVE-2

PSI: 5000 PSI Mix: PAVE 04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE 1	STONE 2	STONE 3	STONE 4	SAND	PASTE	TOTAL	AGGR
1-1/2 "	96.0						0.6	0.9
1 "	29.0	100.0	100.0				10.5	14.6
3/4 "	7.0	99.0	-	100.0			5.9	8.2
1/2 "	3.0	71.0	-	-			7.8	10.9
3/8 "	3.0	48.0	-	-	100.0		5.9	8.2
# 4	2.0	11.0	-	-	99.0		9.9	13.8
# 8	-	2.0	-	-	79.0		8.3	11.6
# 16	-	-	-	-	60.0		5.9	8.2
# 30	-	-	-	-	46.0		4.0	5.5
# 50	-	-	-	-	18.0		8.0	11.1
# 100	-	-	-	-	3.0		4.3	5.9
# 200	-	-	-	-	-	100.0	0.9	1.2
# 325	-	-	-	-	-	94.9	1.4	-
Liquid	-	-	-	-	-	66.3	8.0	-

MATERIALS DISTRIBUTION CHART BY SIEVE

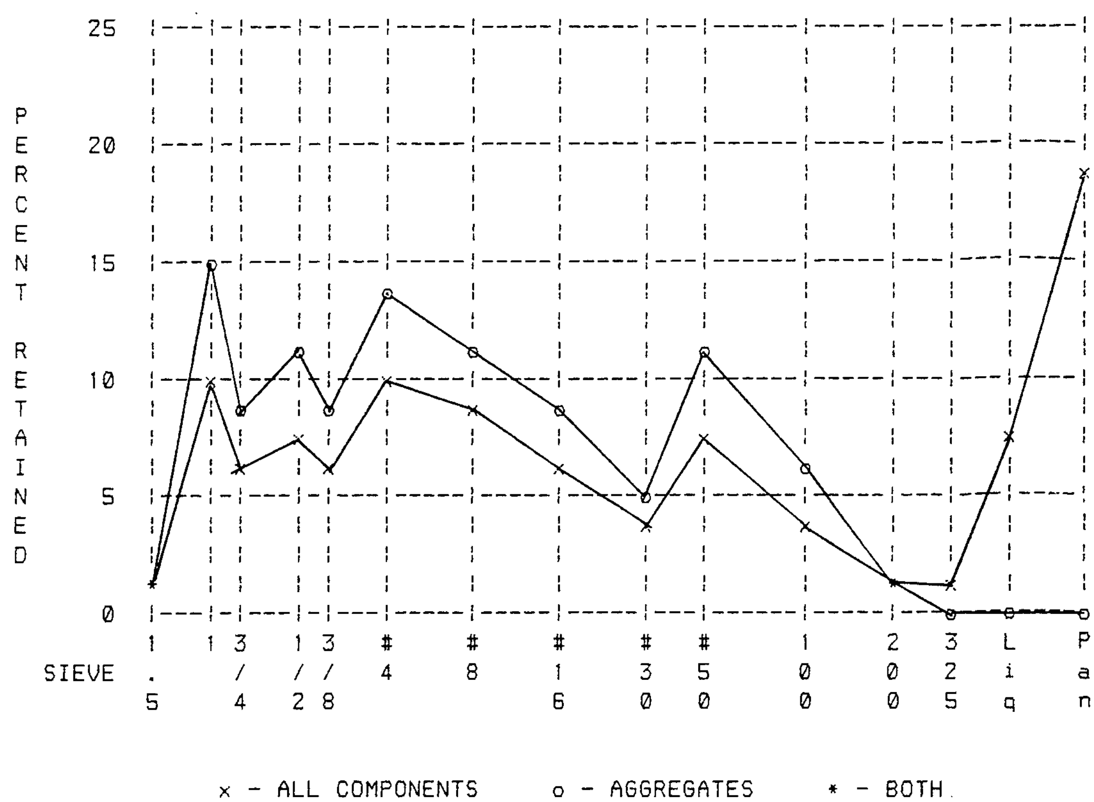


Figure D12. Aggregate particle distribution for mixture PAVE-3

PSI: 5000 PSI Mix: PAVE 04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	98.0			0.8	1.2
1 "	62.0			15.3	21.2
3/4 "	37.0			10.6	14.8
1/2 "	22.0			6.4	8.9
3/8 "	12.0	100.0		4.2	5.9
# 4	2.0	99.0		4.5	6.3
# 8	-	79.0		6.8	9.4
# 16	-	60.0		5.6	7.8
# 30	-	46.0		4.1	5.7
# 50	-	18.0		8.3	11.5
# 100	-	3.0		4.4	6.2
# 200	-	-	100.0	0.9	1.2
# 325	-	-	94.9	1.4	-
Liquid	-	-	66.3	8.0	-

MATERIALS DISTRIBUTION CHART BY SIEVE

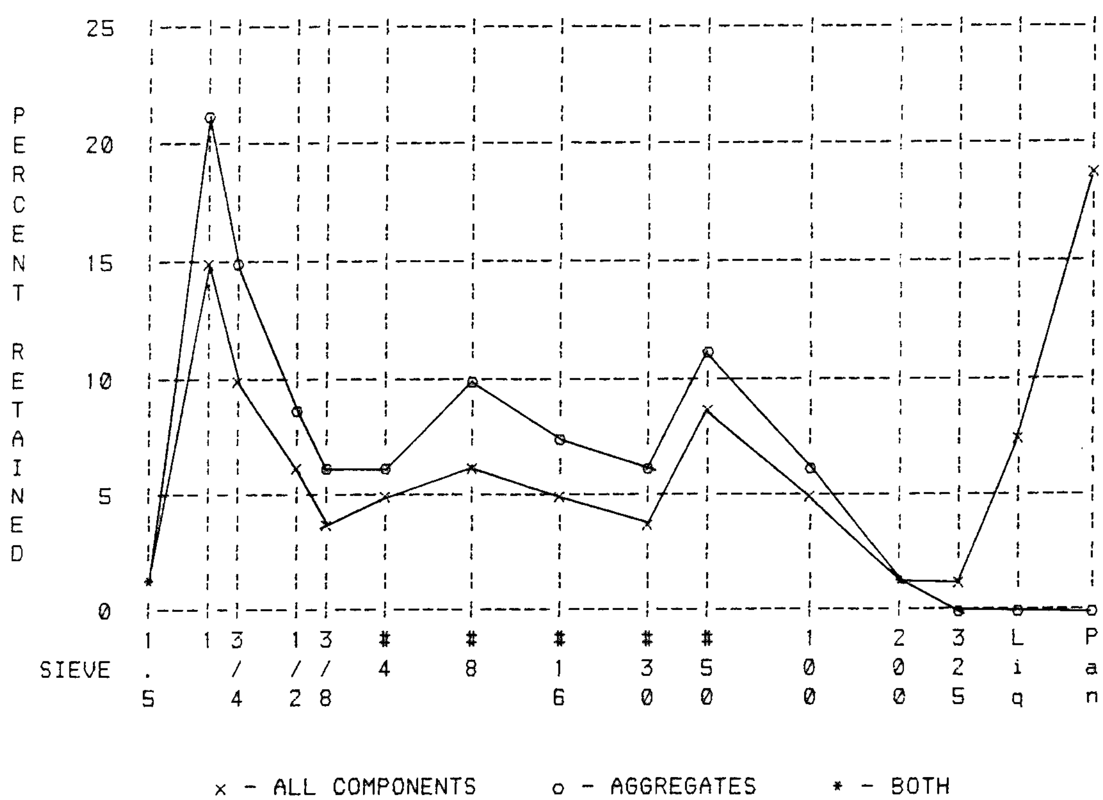


Figure D13. Aggregate particle distribution for mixture PAVE-4

PSI: 5000 PSI Mix: PAVE 04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	99.0			0.4	0.6
1 "	80.0			8.2	11.4
3/4 "	68.0			5.2	7.2
1/2 "	44.0			10.4	14.4
3/8 "	28.0	100.0		6.9	9.6
# 4	3.0	99.0		11.1	15.4
# 8	-	79.0		7.1	9.8
# 16	-	60.0		5.5	7.6
# 30	-	46.0		4.0	5.6
# 50	-	18.0		8.1	11.2
# 100	-	3.0		4.3	6.0
# 200	-	-	100.0	0.9	1.2
# 325	-	-	94.9	1.4	-
Liquid	-	-	66.3	8.0	-

MATERIALS DISTRIBUTION CHART BY SIEVE

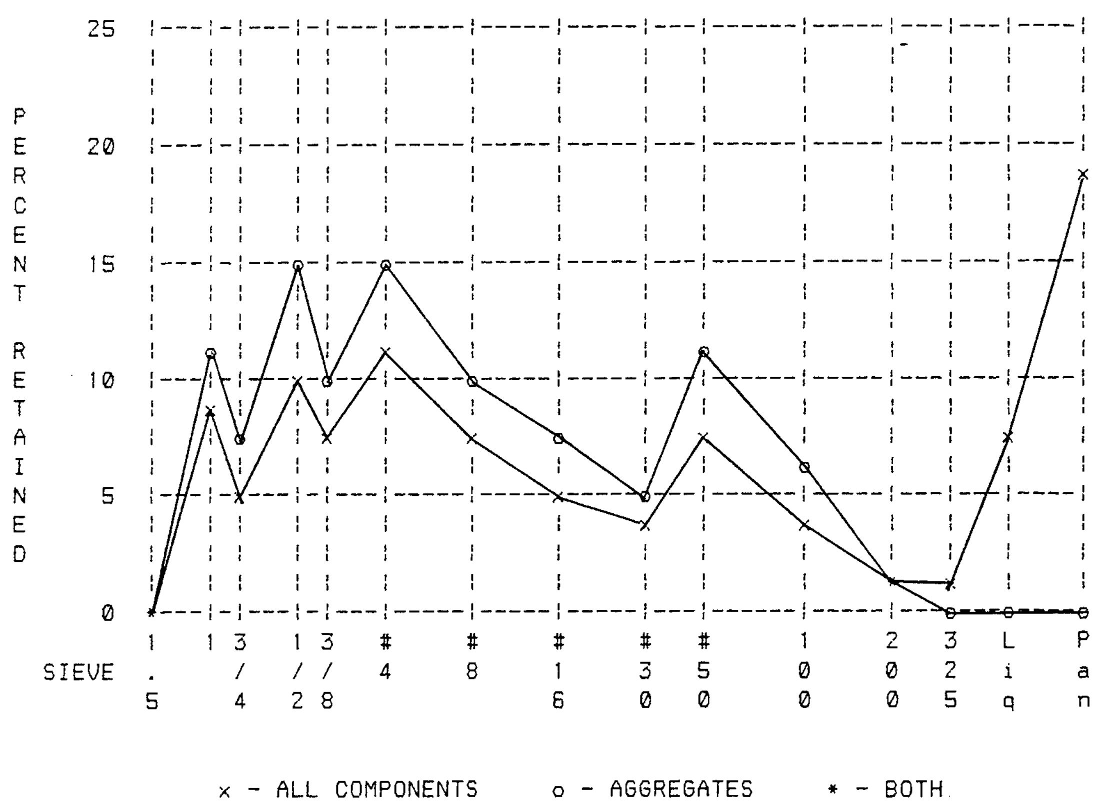


Figure D14. Aggregate particle distribution for mixture PAVE-5

PSI: 5000 PSI   Mix: PAVE   04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE 1	STONE 2	STONE 3	STONE 4	SAND	PASTE	TOTAL	AGGR
1-1/2 "	96.0						0.6	0.9
1 "	29.0	100.0	100.0				10.5	14.5
3/4 "	7.0	99.0	-	100.0			5.9	8.1
1/2 "	3.0	71.0	-	-			7.8	10.8
3/8 "	3.0	48.0	-	-	100.0		5.9	8.2
# 4	2.0	11.0	-	-	99.0		9.9	13.8
# 8	-	2.0	-	-	79.0		8.4	11.6
# 16	-	-	-	-	60.0		6.0	8.3
# 30	-	-	-	-	46.0		4.0	5.6
# 50	-	-	-	-	18.0		8.0	11.1
# 100	-	-	-	-	3.0		4.3	6.0
# 200	-	-	-	-	-	100.0	0.9	1.2
# 325	-	-	-	-	-	95.0	1.4	-
Liquid	-	-	-	-	-	66.4	7.9	-

MATERIALS DISTRIBUTION CHART BY SIEVE

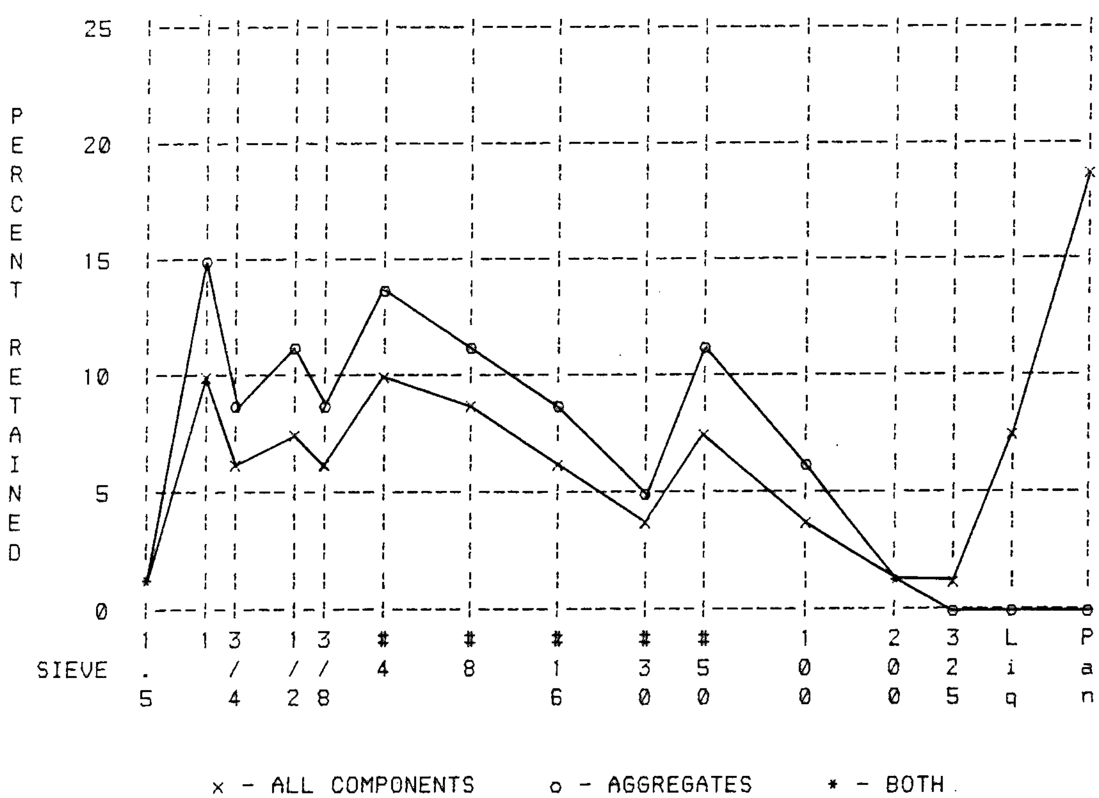


Figure D15. Aggregate particle distribution for mixture PAVE-31

PSI: 5000 PSI Mix: PAVE 04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	98.0			0.9	1.2
1 "	62.0			15.3	21.0
3/4 "	37.0			10.6	14.6
1/2 "	22.0			6.4	8.7
3/8 "	12.0	100.0		4.3	5.8
# 4	2.0	99.0		4.6	6.2
# 8	-	79.0		7.0	9.5
# 16	-	60.0		5.8	7.9
# 30	-	46.0		4.3	5.8
# 50	-	18.0		8.5	11.7
# 100	-	3.0		4.6	6.3
# 200	-	-	100.0	0.9	1.3
# 325	-	-	95.0	1.3	-
Liquid	-	-	66.6	7.6	-

MATERIALS DISTRIBUTION CHART BY SIEVE

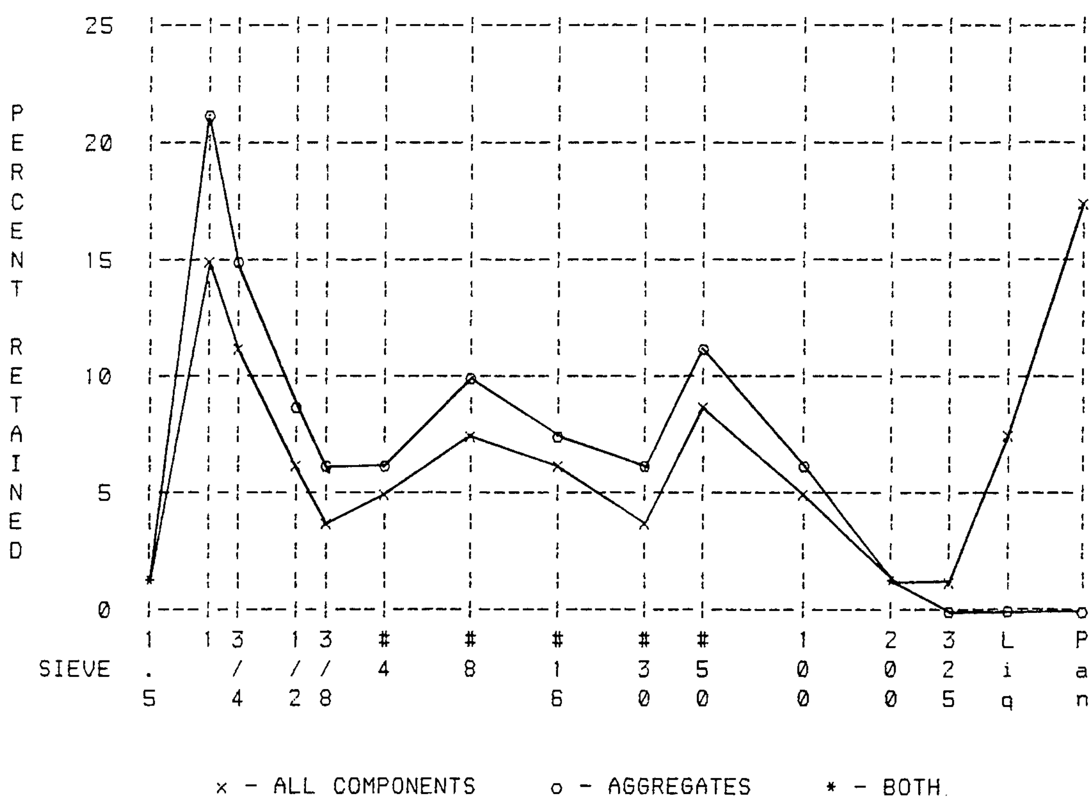


Figure D16. Aggregate particle distribution for mixture PAVE-41

PSI: 5000 PSI   Mix: PAVE   04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	99.0			0.4	0.6
1 "	80.0			8.2	11.3
3/4 "	68.0			5.2	7.2
1/2 "	44.0			10.4	14.3
3/8 "	28.0	100.0		6.9	9.5
# 4	3.0	99.0		11.1	15.3
# 8	-	79.0		7.2	9.9
# 16	-	60.0		5.6	7.7
# 30	-	46.0		4.1	5.7
# 50	-	18.0		8.2	11.3
# 100	-	3.0		4.4	6.1
# 200	-	-	100.0	0.9	1.2
# 325	-	-	95.0	1.4	-
Liquid	-	-	66.5	7.8	-

MATERIALS DISTRIBUTION CHART BY SIEVE

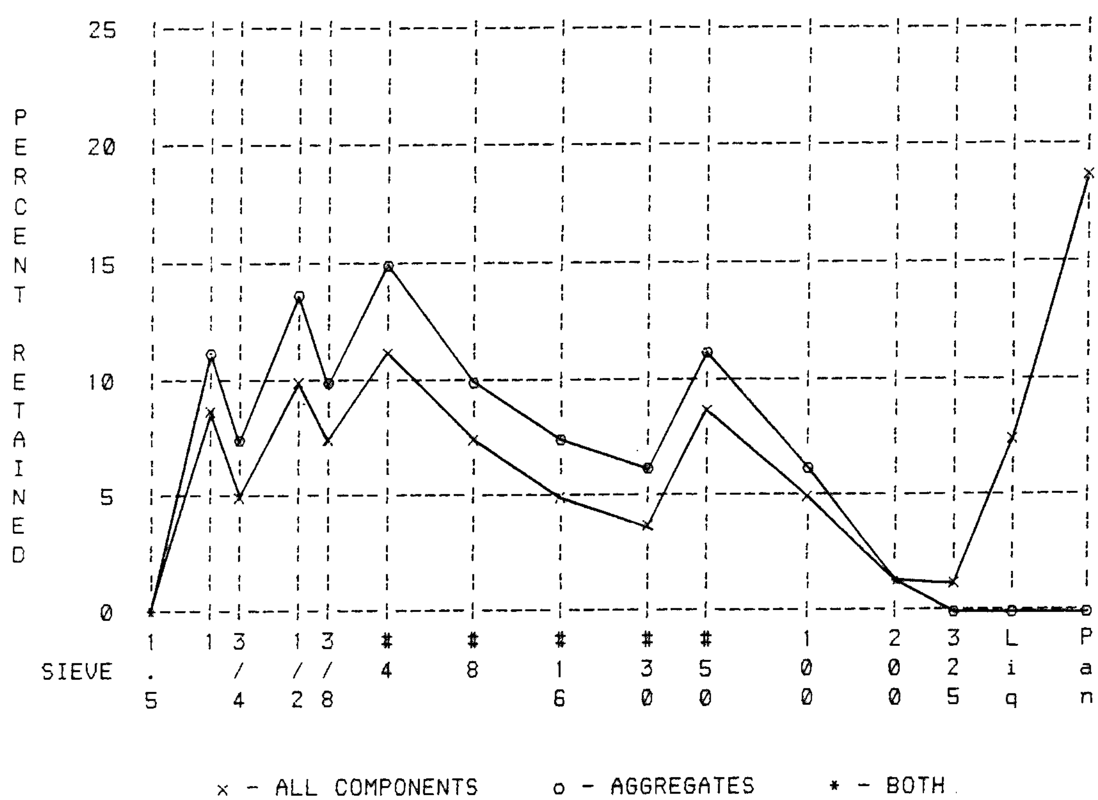


Figure D17. Aggregate particle distribution for mixture PAVE-51

PSI: 4000 PSI   Mix: PAVE   04/24/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "	98.0			0.9	1.2
1 "	62.0			15.5	21.6
3/4 "	53.0			3.9	5.4
1/2 "	44.0			3.9	5.4
3/8 "	20.0	100.0		10.4	14.4
# 4	2.0	93.0		9.8	13.6
# 8	-	82.0		4.0	5.6
# 16	-	70.0		3.5	4.8
# 30	-	46.0		6.9	9.6
# 50	-	6.0		11.5	16.0
# 100	-	-		1.7	2.4
# 200	-	-	100.0	-	-
# 325	-	-	94.9	1.4	-
Liquid	-	-	66.3	8.0	-

MATERIALS DISTRIBUTION CHART BY SIEVE

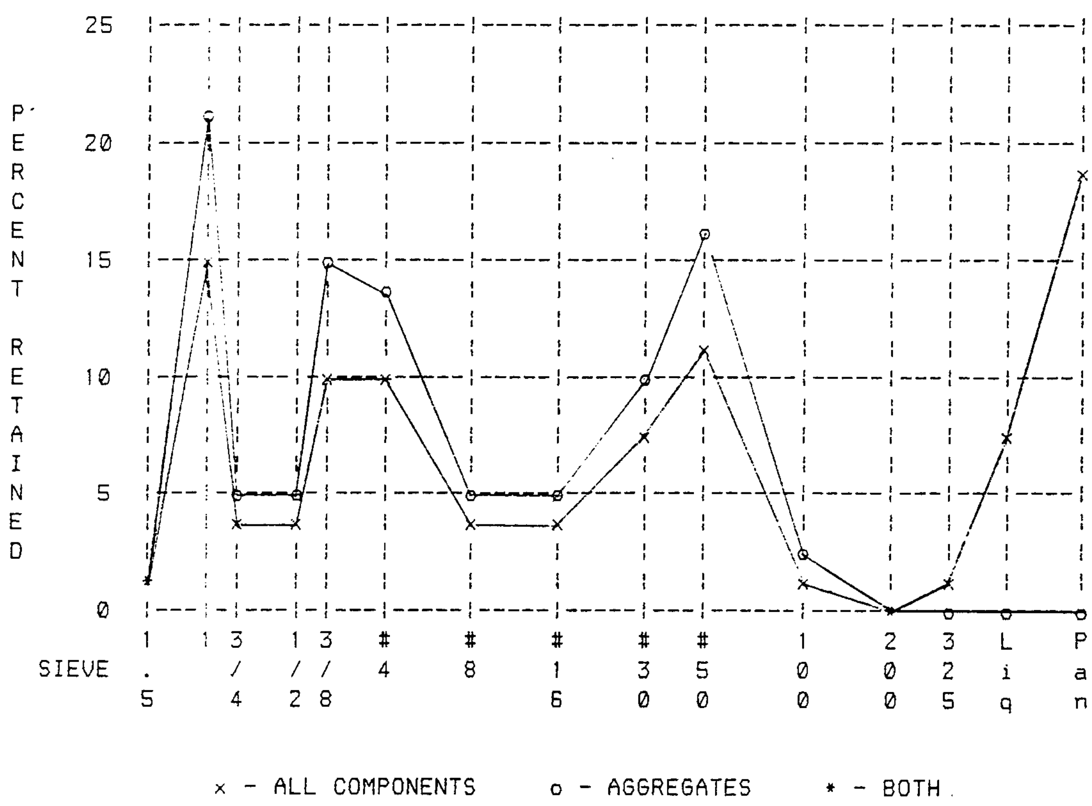


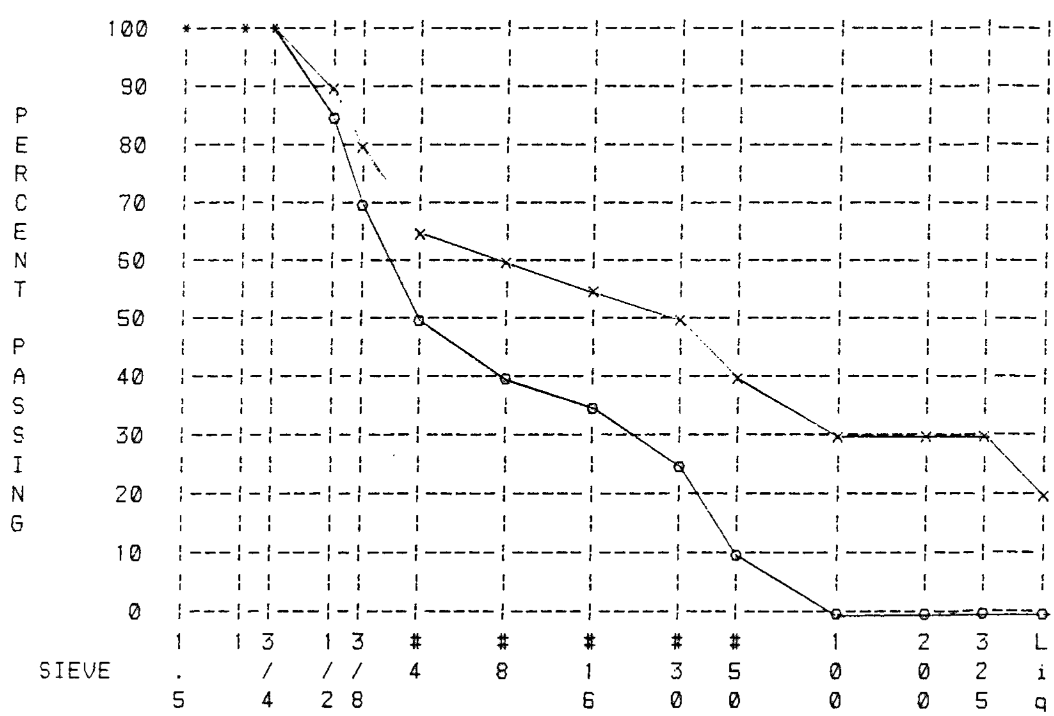
Figure D18. Aggregate particle distribution for mixture PAVE-6

PSI: 4000 PSI Mix: PUMP 04/17/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND 1	SAND 2	PASTE	TOTAL	AGGR
1-1/2 "					100.0	100.0
1 "	100.0				100.0	100.0
3/4 "	99.0				99.6	99.5
1/2 "	71.0				89.3	84.6
3/8 "	48.0	100.0			80.8	72.4
# 4	11.0	99.0			66.9	52.5
# 8	2.0	79.0	100.0		58.6	40.7
# 16	-	60.0	99.0		53.2	32.8
# 30	-	46.0	94.0		49.3	27.3
# 50	-	18.0	38.0		37.8	10.8
# 100	-	3.0	2.0		31.2	1.3
# 200	-	-	-	100.0	30.3	-
# 325	-	-	-	96.0	29.0	-
Liquid	-	-	-	68.9	20.8	-

GRADATION CHART



x - ALL COMPONENTS o - AGGREGATES * - BOTH

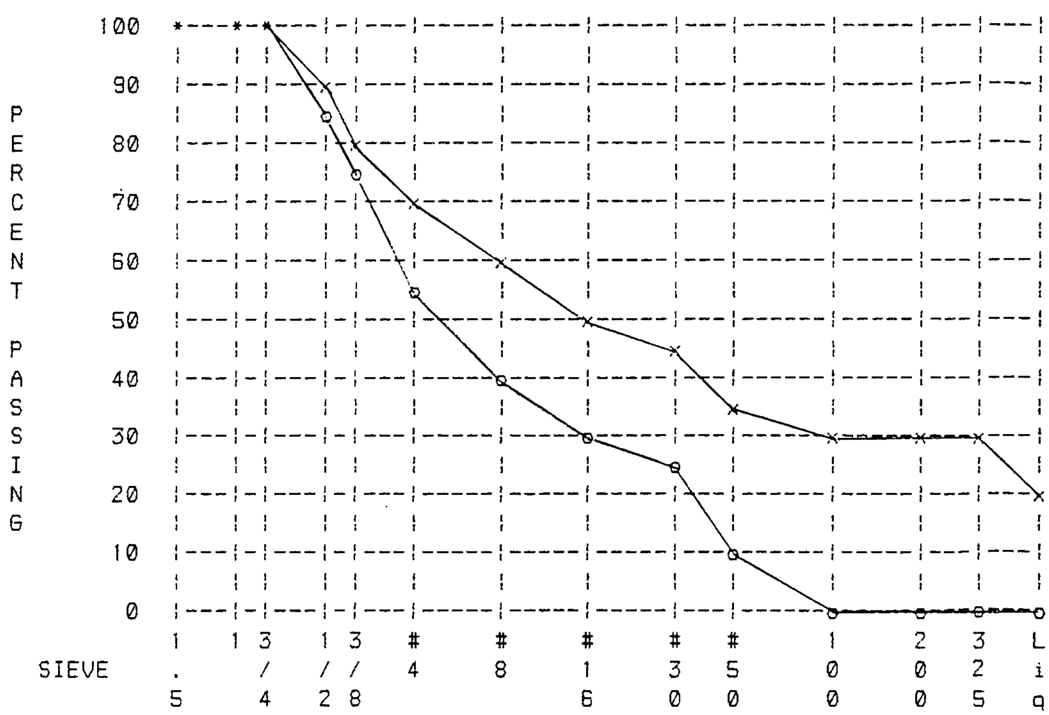
Figure D19. Combined aggregate grading for mixture PUMP-11

PSI: 4000 PSI Mix: PUMP 04/17/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "				100.0	100.0
1 "	100.0			100.0	100.0
3/4 "	99.0			99.6	99.5
1/2 "	71.0			89.7	85.2
3/8 "	48.0	100.0		81.5	73.5
# 4	11.0	99.0		68.0	54.1
# 8	2.0	79.0		58.0	39.7
# 16	-	60.0		50.8	29.4
# 30	-	46.0		46.0	22.5
# 50	-	18.0		36.4	8.8
# 100	-	3.0		31.3	1.5
# 200	-	-	100.0	30.3	-
# 325	-	-	96.0	29.0	-
Liquid	-	-	68.9	20.8	-

GRADATION CHART



x - ALL COMPONENTS o - AGGREGATES * - BOTH

Figure D20. Combined aggregate grading for mixture PUMP-2

PSI: 4000 PSI Mix: PUMP 04/25/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "				100.0	100.0
1 "	100.0			100.0	100.0
3/4 "	99.0			99.6	99.5
1/2 "	71.0			89.6	85.2
3/8 "	48.0	100.0		81.3	73.5
# 4	11.0	99.0		67.7	54.1
# 8	2.0	79.0		57.5	39.7
# 16	-	60.0		50.2	29.4
# 30	-	46.0		45.4	22.5
# 50	-	18.0		35.7	8.8
# 100	-	3.0		30.5	1.5
# 200	-	-	100.0	29.5	-
# 325	-	-	96.0	28.3	-
Liquid	-	-	69.1	20.4	-

GRADATION CHART

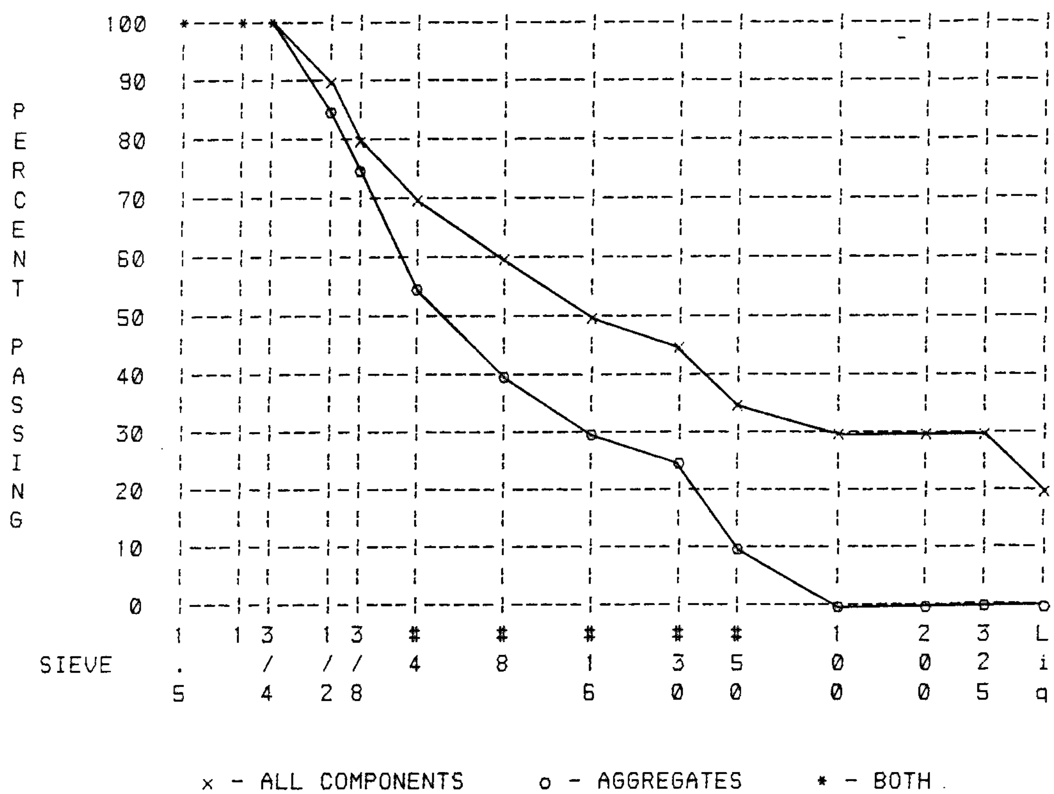


Figure D21. Combined aggregate grading for mixture PUMP-21

PSI: 4000 PSI Mix: PUMP 04/18/91

FULL GRADATION ANALYSIS

SIEVE	STONE	SAND 1	SAND 2	PASTE	TOTAL	AGGR
1-1/2 "					100.0	100.0
1 "	100.0				100.0	100.0
3/4 "	99.0				99.6	99.4
1/2 "	71.0				88.5	83.5
3/8 "	48.0	100.0			79.3	70.3
# 4	11.0	99.0			64.4	48.9
# 8	2.0	79.0	100.0		56.3	37.3
# 16	-	60.0	99.0		51.2	30.0
# 30	-	46.0	94.0		47.6	24.9
# 50	-	18.0	38.0		37.2	9.9
# 100	-	3.0	2.0		31.1	1.2
# 200	-	-	-	100.0	30.3	-
# 325	-	-	-	96.0	29.0	-
Liquid	-	-	-	68.9	20.8	-

GRADATION CHART

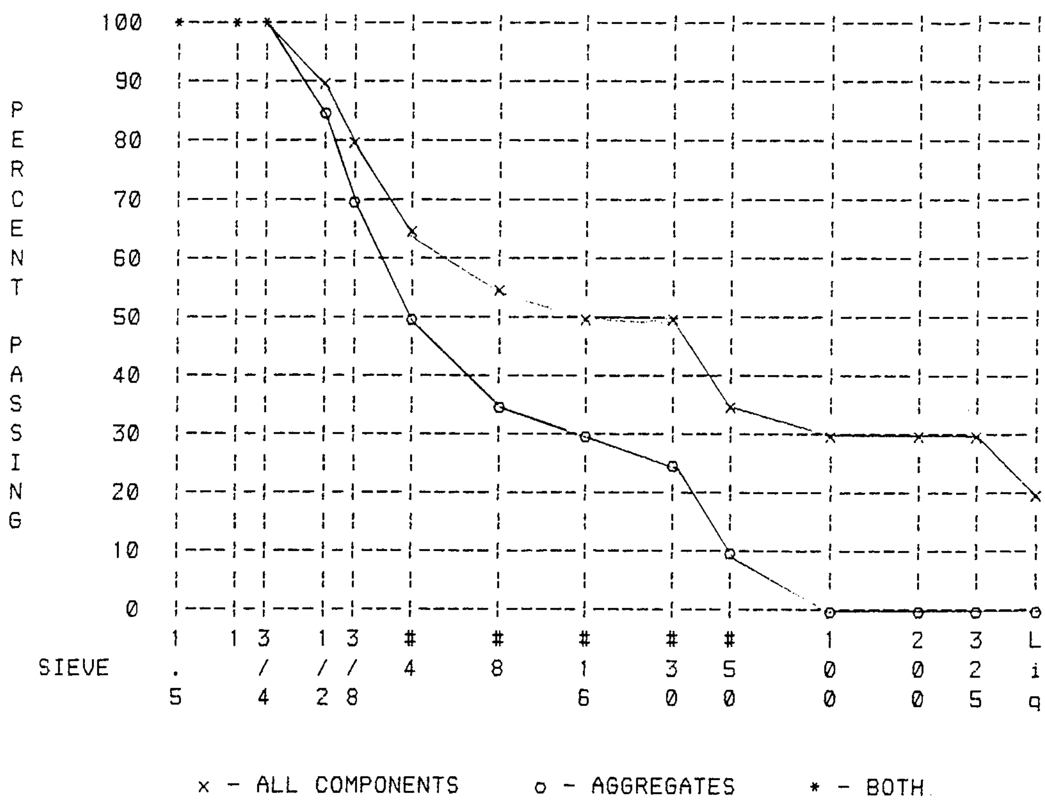


Figure D22. Combined aggregate grading for mixture PUMP-3

PSI: 4000 PSI Mix: PUMP 04/17/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND 1	SAND 2	PASTE	TOTAL	AGGR
1-1/2 "					0.0	-
1 "	100.0				-	-
3/4 "	99.0				0.4	0.5
1/2 "	71.0				10.3	14.8
3/8 "	48.0	100.0			8.5	12.2
# 4	11.0	99.0			13.9	20.0
# 8	2.0	79.0	100.0		8.2	11.8
# 16	-	60.0	99.0		5.5	7.8
# 30	-	46.0	94.0		3.8	5.5
# 50	-	18.0	38.0		11.5	16.5
# 100	-	3.0	2.0		6.7	9.5
# 200	-	-	-	100.0	0.9	1.3
# 325	-	-	-	96.0	1.2	-
Liquid	-	-	-	68.9	8.2	-

MATERIALS DISTRIBUTION CHART BY SIEVE

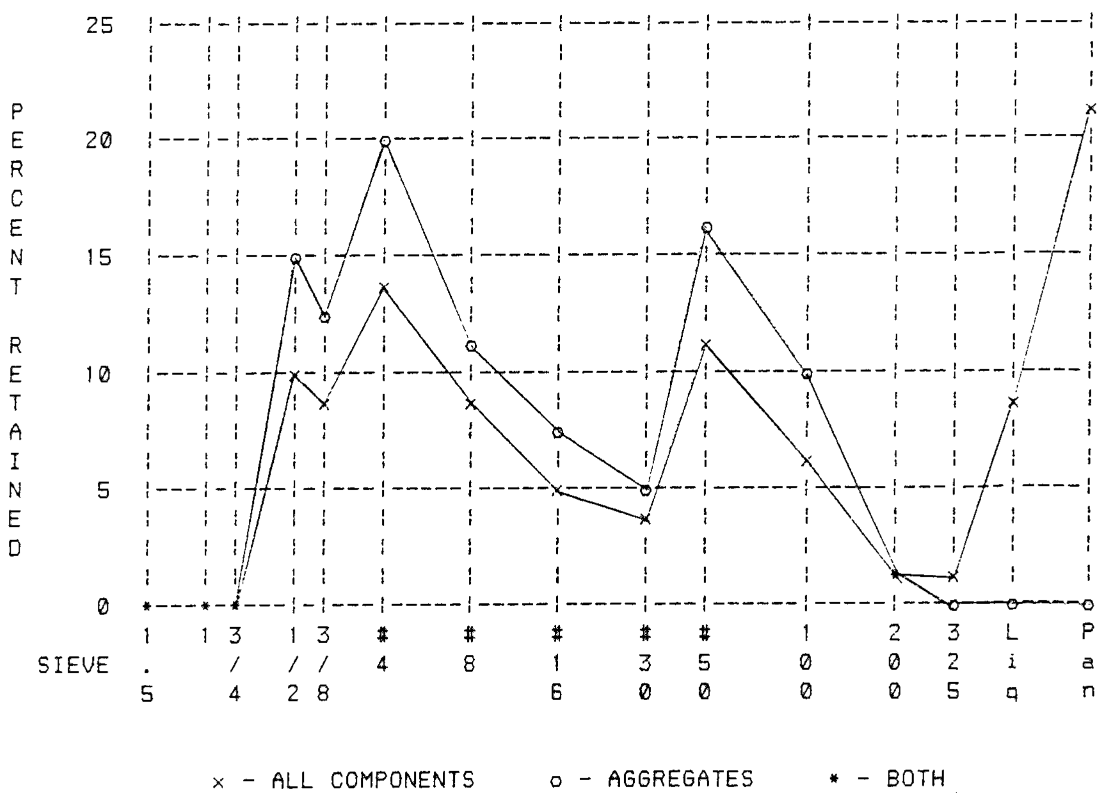


Figure D23. Combined aggregate grading for mixture PUMP-11

PSI: 4000 PSI Mix: PUMP 04/17/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "				-	-
1 "	100.0			-	-
3/4 "	99.0			0.4	0.5
1/2 "	71.0			10.0	14.3
3/8 "	48.0	100.0		8.2	11.7
# 4	11.0	99.0		13.5	19.4
# 8	2.0	79.0		10.0	14.4
# 16	-	60.0		7.2	10.3
# 30	-	46.0		4.8	6.9
# 50	-	18.0		9.6	13.7
# 100	-	3.0		5.1	7.4
# 200	-	-	100.0	1.0	1.5
# 325	-	-	96.0	1.2	-
Liquid	-	-	68.9	8.2	-

MATERIALS DISTRIBUTION CHART BY SIEVE

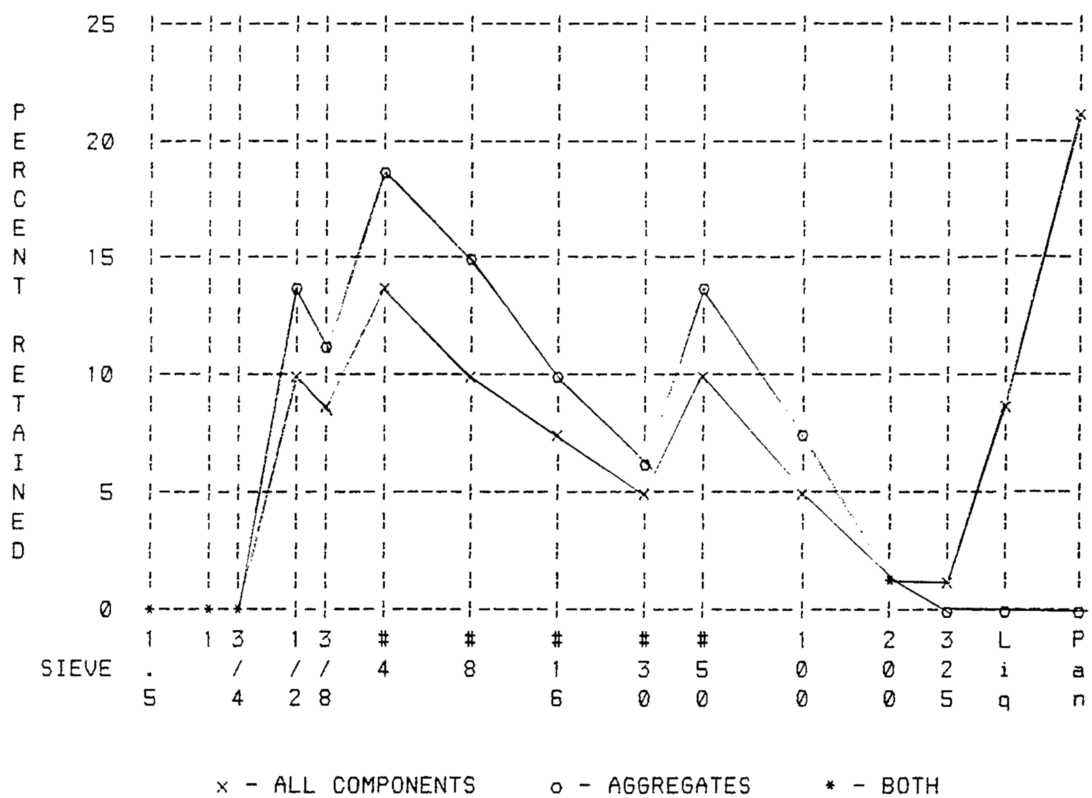


Figure D24. Combined aggregate grading for mixture PUMP-2

PSI: 4000 PSI Mix: PUMP 04/25/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND	PASTE	TOTAL	AGGR
1-1/2 "				0.0	-
1 "	100.0			-	-
3/4 "	99.0			0.4	0.5
1/2 "	71.0			10.1	14.3
3/8 "	48.0	100.0		8.3	11.7
# 4	11.0	99.0		13.6	19.4
# 8	2.0	79.0		10.1	14.4
# 16	-	60.0		7.3	10.3
# 30	-	46.0		4.8	6.9
# 50	-	18.0		9.7	13.7
# 100	-	3.0		5.2	7.4
# 200	-	-	100.0	1.0	1.5
# 325	-	-	96.0	1.2	-
Liquid	-	-	69.1	7.9	-

MATERIALS DISTRIBUTION CHART BY SIEVE

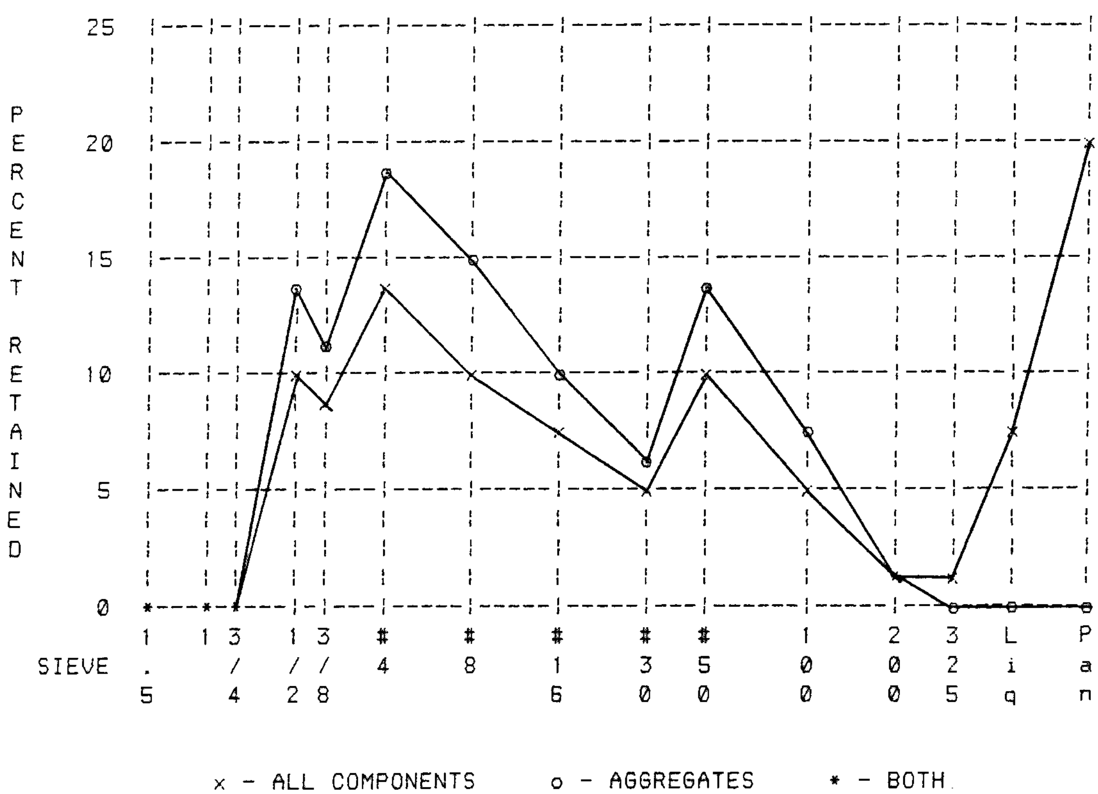


Figure D25. Combined aggregate grading for mixture PUMP-21

PSI: 4000 PSI Mix: PUMP 04/18/91

MATERIALS DISTRIBUTION

SIEVE	STONE	SAND 1	SAND 2	PASTE	TOTAL	AGGR
1-1/2 "					-	-
1 "	100.0				-	-
3/4 "	99.0				0.4	0.6
1/2 "	71.0				11.1	16.0
3/8 "	48.0	100.0			9.1	13.1
# 4	11.0	99.0			14.9	21.4
# 8	2.0	79.0	100.0		8.1	11.6
# 16	-	60.0	99.0		5.1	7.4
# 30	-	46.0	94.0		3.5	5.0
# 50	-	18.0	38.0		10.5	15.0
# 100	-	3.0	2.0		6.1	8.7
# 200	-	-	-	100.0	0.8	1.2
# 325	-	-	-	96.0	1.2	-
Liquid	-	-	-	68.9	8.2	-

MATERIALS DISTRIBUTION CHART BY SIEVE

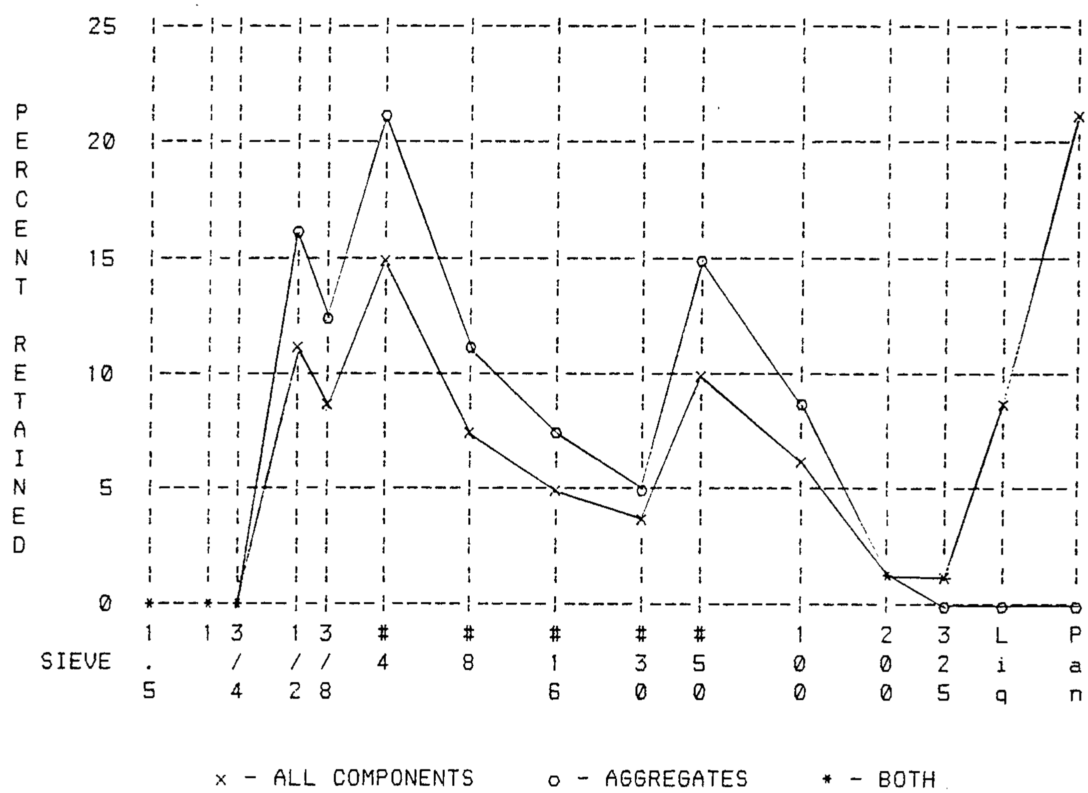


Figure D26. Aggregate particle distribution for mixture PUMP-3

Appendix E
Two-Point Workability Curves — SeeMIX Laboratory Evaluation

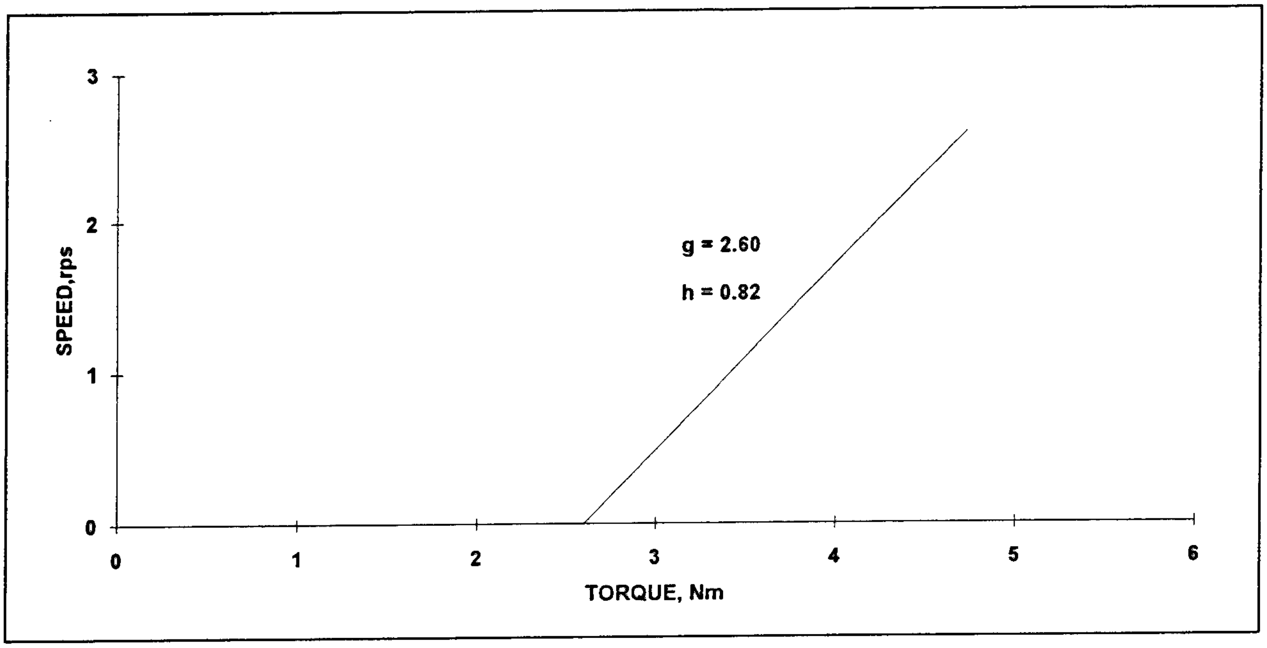


Figure E1. Two-point workability curve for mixture PUMP-1

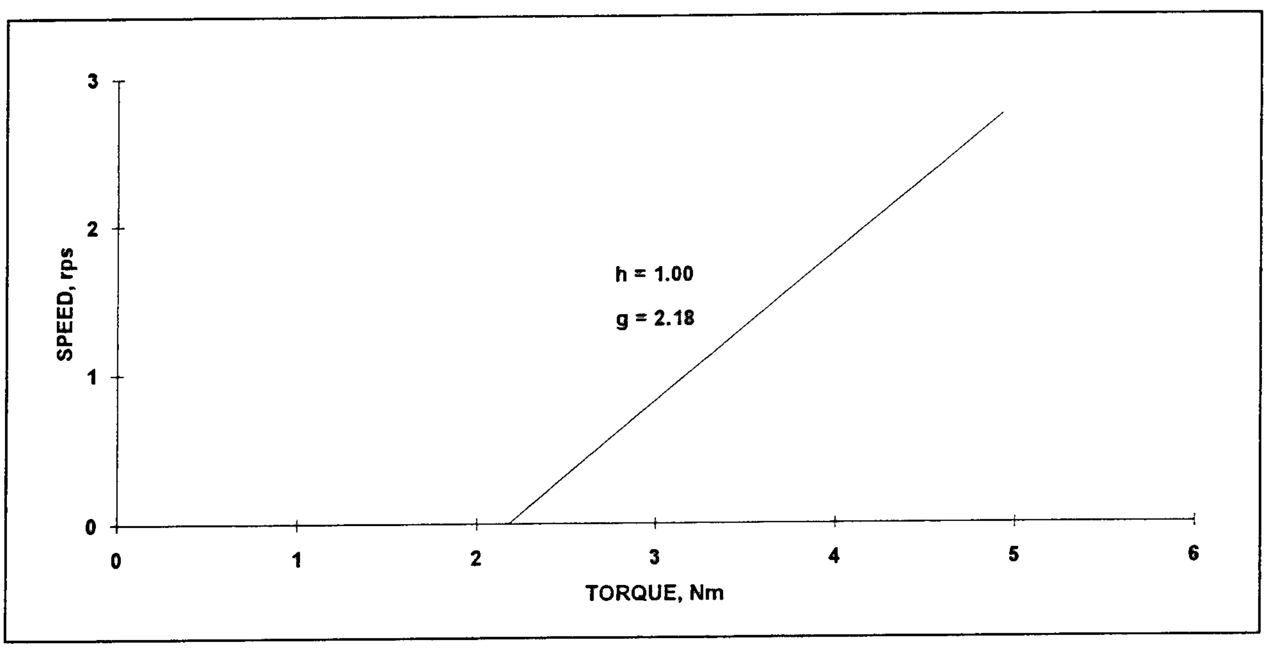


Figure E2. Two-point workability curve for mixture PUMP-11

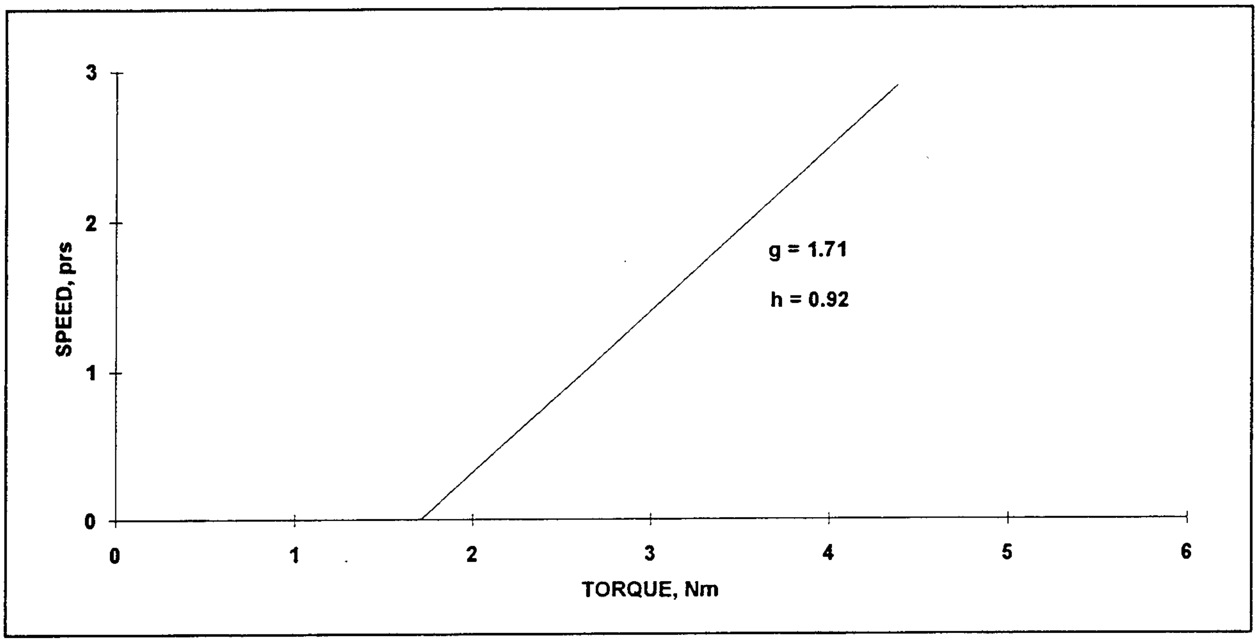


Figure E3. Two-point workability curve for mixture PUMP-2.

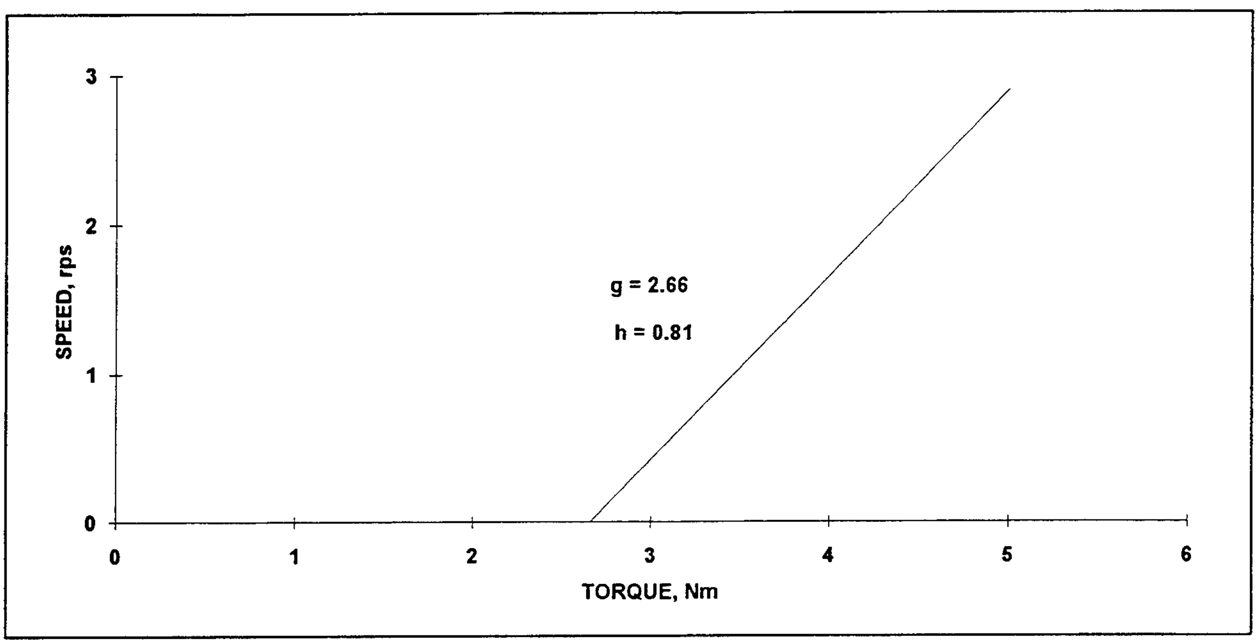


Figure E4. Two-point workability curve for mixture PUMP-21

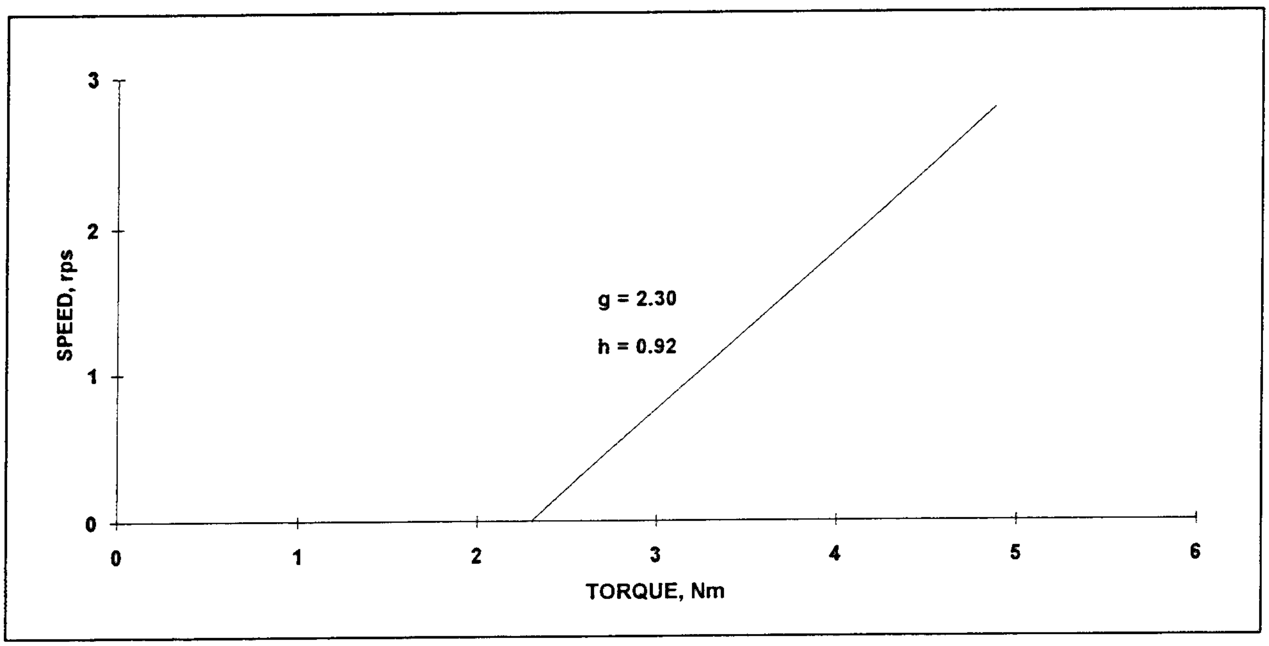


Figure E5. Two-point workability curve for mixture PUMP-3

Appendix F
Individual Fresh Concrete Test Results for Blue River Paved Reach Project

Table F1 Fresh Concrete Test Results for Blue River Paved Reach					
Mixture	Batch No.	Slump mm (in.)	Unit Weight kg/m^3 (lb/ft^3)	Air Content percent	Bleed percent
BR-1	1	165 (6-1/2)	2,249 (140.4)	8.2	1.1
	2	140 (5-1/2)	2,300 (143.6)	6.4	0.8
	3	130 (5-1/4)	2,319 (144.8)	5.7	0.8
BR-4	1	6 (150)	2,294 (143.2)	6.4	0.5
	2	160 (6-1/4)	2,297 (143.4)	6.4	0.3
	3	140 (5-1/2)	2,313 (144.4)	6.1	0.2

Table F2 Hardened Concrete Test Results for Blue River Paved Reach						
		Compressive Strength, MPa (psi)		Underwater Abrasion Loss (@72 hr), m^3	Charge Passed coulombs	Length Change percent
Mixture	Batch No.	7-day	28-day			
BR-1	1	29.8 (4,320)	37.8 (5,480)	0.000747	3,043	0.0249
	2	33.0 (4,780)	41.0 (5,940)	0.000661	3,348	0.0280
	3	33.2 (4,810)	41.4 (6,010)	0.000650	3,094	0.0262
BR-4	1	34.8 (5,040)	41.4 (6,010)	0.000593	3,184	0.0210
	2	34.1 (4,950)	42.2 (6,120)	0.000556	3,203	0.0319
	3	33.0 (4,780)	42.7 (6,190)	0.000565	3,483	0.0219

Appendix G
Technology Transfer Activities by Shilstone Software Co.

ARTICLES DEVELOPED BY SHILSTONE UNDER CPAR

"Concrete Pavement - Specifications by Modeling," presented at ASCE Materials Congress, August 1990, New York, NY

"Optimizing Concrete Mixtures," *Concrete International*, June 1990, pp. 33-39, James M. Shilstone, published by American Concrete Institute, Detroit, MI

"Doing More with Less Optimizing Concrete Mix," *Better Roads*, August 1990, pp. 18-25, *Better Roads* staff, Rosemont, IL

"Hawkeye Producer Spurns Loose Use of Chemical Agents," *Engineering News-Record*, Jan. 21, 1991, p. 38, authors: Rob McManamy, David B. Rosenbaum, McGraw Hill Publications, New York, NY

"High Performance Concrete: What Does It Mean?," *Concrete Products*, March 1991, p. 11, Chicago, IL

"Understanding Concrete Mixtures," *Concrete Products*, June 1991, pp. 41-45, James M. Shilstone, Chicago, IL

"Customize Every Concrete Batch with Computers," *Concrete Construction*, June 1991, pp. 477-479, James M. Shilstone & James M. Shilstone, Jr., Aberdeen Group, Chicago, IL

"Should We Use Contractor Performance Standards?," *Better Roads*, August 1992, pp. 14-16, James M. Shilstone, Rosemont, IL

"Quality Management for Concrete Pavement under Performance Standards," *Transportation Research Record* #1340, 1992, pp. 48-55, Transportation Research Board, Washington, DC

"The Concrete Mixture: The Key to Pavement Durability," Proceedings of the Fifth International Conference on Concrete Pavement Design and Rehabilitation," pp. 211-216, James M. Shilstone, Purdue University, W. Lafayette, IN

"Contractors "See" Better Results with Statistical Software," *Asphalt Contractor*, November 1993, pp. 20, 24, 64, James M. Shilstone, Independence, MO

"Changes in Concrete Aggregate Standards," *The Construction Specifier*, July 1994, pp. 119-128, James M. Shilstone, Alexandria, VA

"Needed - Paradigm Shifts in the Technology for Normal Strength Concrete," *Concrete Technology Past, Present and Future - Proceedings of the V. Mohan Malhotra Symposium, ACI SP-144*, pp. 61-84, James M. Shilstone & James M. Shilstone, Jr., American Concrete Institute, Detroit, MI

"High Performance Concrete Mixtures for Durability," *ACI SP 140-14: High Performance Concrete*, pp. 281-305, James M. Shilstone & James M. Shilstone, Jr., American Concrete Institute Detroit, MI

Figure G1. Articles prepared by Shilstone Software Co. during the CPAR project

TECHNOLOGY TRANSFER FUNCTIONS WITH SHILSTONE PARTICIPATION

EVENT LOCATION	DATES	# ATTENDEES	# HEARD PRESENTATION
ASTM Convention			
Orlando, FL	Jan. 1-6, 1990	committees only	committees
TRB Convention - "Mixture Optimization for Fast-Track"			
Wash., DC	Jan. 7-12, 1990	10,000	120
Oklahoma Pavement Seminar -"Better Aggregate Gradations"			
Oklahoma City	Jan. 16-17, 1990	150	150
World of Concrete - trade show booth			
Houston, TX	Jan. 20-23, 1990	20,000	500
Con/Agg Show - trade show booth			
Las Vegas, NV	Jan. 29-Feb. 1, 1990	20,000	400
Iowa-Minnesota ACI Chapter seminar - "Optimized Concrete Aggregates"			
Des Moines, IA	Feb., 1990	60	60
Nebraska Concrete & Aggregate Producer's Annual Meeting - "Concrete Mixture Optimization"			
Lincoln, NE	Feb., 1990	175	175
Empire State Concrete & Aggregate Producer's Annual Meeting			
Rochester, NY	Mar. 5-9, 1990	150	50
American Concrete Institute Spring Convention - "Statistics Beyond Standard Deviation" "Introducing - SmartPlant"			
Toronto, ON	Mar. 18-22, 1990	1,200	120
Carolina Ready Mix Association - "Combined Aggregate Grading"			
Hilton Head, SC	April, 1990	300	250
ASTM meeting - committee meetings only			
San Francisco, CA	June 6-20, 1990	-	-
Shilstone Software training session			
San Francisco, CA	June 20, 1990	18	18
American Society for Civil Engineers - Materials Congress - paper published			
Denver, CO	Aug. 11-15, 1990	500	25
New Orleans ACI Chapter Meeting - "Concrete Mix Optimization"			
New Orleans, LA	Sept. 20, 1990	20	20
Shilstone Software educational session			
New Orleans, LA	Sept. 21, 1990	25	25
ACI 126, Concrete Materials Database Format organizational committee meeting			
Gaithersburg, MD	Sept. 11-15, 1990	8	8
American Concrete Institute Fall Convention - attended			
Philadelphia, PA	Nov. 10-15, 1990	1,200	-
American Concrete Pavement Assn.			
Phoenix, AZ	Nov. 29-Dec. 1, 1990	450	-
Shilstone Software Co. workshop			
Dallas, TX	Dec. 7, 1990	105	105
ASTM - committee meetings			
San Antonio, TX	Dec. 2-3, 1990	-	-
TRB			
Washington, DC	Jan. 8-12, 1991	10,000	-
World of Concrete - trade show booth			
Las Vegas, NV	Jan. 27-31, 1991	20,000	500
National Asphalt Pavement Assn. - trade show booth			
Dallas, TX	Feb. 9-14, 1991	2,000	300

Figure G2. Meetings, seminars, and workshops in which Shilstone Software Co. participated (Sheet 1 of 3)

TECHNOLOGY TRANSFER FUNCTIONS WITH SHILSTONE PARTICIPATION

EVENT LOCATION	DATES	# ATTENDEES	# HEARD PRESENTATION
American Concrete Institute Spring Convention - "Performance Specifications" "Concrete Mix Modeling" "Concrete & Statistics"			
Boston, MA	Mar. 16-21, 1991	1,200	80
Mountain States Concrete Pavement Conference - "Concrete Mixture Management by Computer"			
Denver, CO	Mar. 26-29, 1991	400	75
Northern Arizona Concrete Conference - "Making Adjustments in Concrete Mixtures"			
Flagstaff, AZ	Feb. 26 - Mar. 1, 1991	350	350
Phoenix ACI Chapter meeting - "Concrete Mix Optimization"			
Phoenix, AZ	Can't determine dates	75	75
National Fast Track/Mix Design Conference			
Kansas City, KS	April 1-3, 1991	400	-
Seattle ACI Chapter meeting - "Concrete Mix Optimization"			
Seattle, WA	May 5, 1991	80	80
Univ. of Missouri at Rolla - "Concrete Mix Optimization"			
Rolla, MO	May 11, 1991	350	350
RILEM Conference "Concrete Quality Control" (attending only)			
Ghent, Belgium	June 8-16, 1991	150	N/A
Shilstone Software training workshps			
Albany, NY	Can't determine dates	60	60
Michigan Concrete Assn. Show - trade show booth, "Concrete Mix Optimization"			
Detroit, MI	Can't determine dates	125	125
Northwest Paving Conference - Optimized Mixes for Pavements"			
Boise, ID	Oct. 29-Nov. 3, 1991	275	275
4R Show - "A Dynamic On-Line Approach to Project Management for Production of Concrete"			
Cincinnati, OH	Dec. 10-13, 1991	5,000	20
ASTM presentation on seeMAT-C for Committee C01.27			
San Diego, CA	Dec. 8-12, 1991	20	20
TRB, 1992			
Washington, DC	Jan. 12-16, 1992	10,000	-
Con/Agg Show -trade show booth			
New Orleans, LA	Feb. 2-6, 1992	12,000	400
World of Concrete - trade show booth			
Atlanta, GA	Feb. 16-20, 1992	20,000	500
Fast-Track Construction mtg - TXDOT committee meeting			
Houston, TX	April 2, 1992	40	-
New York DOT program on Contractor QA/QC (with Empire State Concrete & Aggregates Producers)			
Syracuse, NY	April-June 1992	95	95
RILEM workshop - "Concrete for the Future"			
Helsinki, Finland	Sept. 14-15, 1992	12	12
Virginia Ready Mix Concrete Assn. - "Optimized Concrete Mixtures"			
Wintergreen, VA	July-Sept., 1992	70	70
Portland Cement Association Advanced Concrete Technology class			
Skokie, IL	Dec., 1992	15	15
This was the first of a series of classes taught by Shilstone, continuing twice a year in February and December through 1995		total 100	100

Figure G2. (Sheet 2 of 3)

TECHNOLOGY TRANSFER FUNCTIONS WITH SHILSTONE PARTICIPATION

EVENT LOCATION	DATES	# ATTENDEES	# HEARD PRESENTATION
National Quality Initiative Agreement			
Dallas, TX	Nov. 10, 1992	400	-
TRB Annual Meeting #72, Session #168, - "TQM - Putting Theory into Practice"			
Washington, DC	Jan., 1993	20,000	175
World of Concrete 1993 - "New Concrete Mix Technology"			
New Orleans, LA	Mar., 1993	20,000	500
Iowa Paving Assn. - "Computerized Mix Technology"			
Des Moines, IA	Feb. 10-12, 1993	250	250
Purdue Paving Conference - "Concrete Mixtures & Durability"			
W. Lafayette, IN	April 21-23	500	75
Shilstone Software Hands-On Training Workshop			
Dallas, TX	Spring 1993	20	20
RILEM workshop on "Optimized Concrete Mixtures"			
Warsaw, Poland	May 17-18, 1993	15	15
American Concrete Institute Fall Convention - "10 Commandments for Better Concrete" "Statistical Analysis of Concrete Tests"			
Minneapolis, MN	Fall, 1993	1,200	50
American Coal Ash Assn. - "Pozzolan Statistical Analysis"			
Las Vegas, NV	Oct. 19, 1993	60	60
Shilstone Software Training seminar			
Dallas, TX	Dec. 8-11, 1993	20	20
Con/Agg 1994 - trade show booth - "Optimized Mixture Proportioning"			
Las Vegas, NV	Feb. 6-10, 1994	9,000	400
American Concrete Institute Spring Convention - "Slump from the Consultants Viewpoint "Paradigm Shift in the Technology of Normal Strength Concrete" "Alternative Statistical Methods to Reduce Costs and Control Quality"			
San Francisco, CA	Mar. 20-25, 1994	1,200	150
Shilstone Software Hands-On training workshops			
Dallas, TX	Mar. 9-11, 1994	20	20
Boston, MA	June 9-10, 1994	8	8
Orlando, FL		4	4
Las Vegas, NV		16	16
Detroit, MI		12	12

Figure G2. (Sheet 3 of 3)

seeMix sales from 11/1/89 to 4/24/95 (Under CPAR)

Type	MSt																																					
		AB	AK	AL	AR	AZ	BC	CA	CO	CT	DE	DF	FL	GA	HI	IA	IL	IN	JA	KS	KY	LA	MA	MB	MD	ME	MI	MN	MO	MP	MS	NB	NC	ND	NE	NF	NH	NJ	NM
ADMIX	2	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AGG	5	0	1	0	1	3	0	5	2	1	0	0	1	0	0	1	1	0	1	0	1	0	1	0	2	0	4	3	1	0	1	0	1	0	0	0	0	1	0
aggr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
ASPH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ASPHALT	0	0	1	0	0	2	0	3	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
Assn	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
block	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0
Cement	1	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
CM	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Constr	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Consult	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
consultant	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Contr	2	2	0	0	0	0	1	2	1	0	0	0	0	1	0	4	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	1	0	0	0	1
dealer	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EDUC	1	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2	0	7	0	0	0	6	0	0	0	0	0	1	0	0	0	0	0	0
Engr	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0
equip	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fiber	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fly ash	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
govt	1	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	1	0	0	0	1	1	0	0	0	0	0	0	2	0	1	1	0	0	1	0
Lab	0	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	3	2	0	1	0	2	0	0	2	0	0	0
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Owner	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
pave	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Paving	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC	1	0	0	0	0	1	1	1	0	0	0	0	0	1	0	2	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Premix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pump	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RM	7	2	0	3	3	7	4	16	5	2	0	0	4	1	1	4	4	3	0	12	6	4	3	0	9	1	16	6	7	1	6	1	8	1	0	0	1	2	1
RMB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
RMM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Count	21	6	2	5	5	14	11	33	12	4	1	1	7	3	3	17	6	3	1	15	10	6	12	1	12	2	30	15	12	1	9	5	14	4	2	2	1	4	2

Figure G3. SeeMIX, seeSTAT, and seeMAT-A sales during the CPAR project (Sheet 1 of 6)

seeMix sales from 11/1/89 to 4/24/95 (Under CPAR)

MSt																									
NV	NY	OH	OK	ON	OR	PA	PEI	PR	QB	RI	SC	SD	SO	TN	TRANSVAAL	TX	UT	VA	VT	WA	WI	WV	WY	-	COUNT
0	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	12
1	4	2	0	0	2	1	0	0	0	0	0	1	0	2	0	1	0	6	0	2	1	0	0	0	60
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	6
0	1	0	0	3	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	1	1	0	0	0	15
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	1	0	0	0	0	1	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	0	0	24
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	1	0	0	0	0	0	0	28
0	3	0	0	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	12
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
2	3	0	2	0	0	0	0	0	0	1	0	0	0	0	0	1	2	2	0	0	1	0	1	0	27
0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	21
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
0	1	2	1	0	1	2	0	0	0	0	1	0	0	0	0	2	1	2	0	1	0	0	0	0	24
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
6	10	9	0	4	5	2	0	2	1	0	3	1	1	6	0	11	4	9	1	7	5	2	0	0	240
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
10	31	20	3	8	10	6	2	3	1	1	6	3	1	9	1	24	9	23	1	12	9	2	1	1	511

Figure G3. (Sheet 2 of 6)

seeMix sales from 11/1/89 to 4/24/95 (Under CPAR)

		MSt																																				
Type		AB	AK	AL	AR	AZ	BC	CA	CO	CT	DE	DF	FL	GA	HI	IA	ID	IL	IN	KS	KY	LA	MA	MB	MD	ME	MI	MN	MO	MS	NB	NC	ND	NE	NF	NH	NJ	NH	NV
ADMIX	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Agg	9	0	1	0	0	3	0	5	1	0	0	0	6	0	0	0	0	0	0	0	2	0	0	0	2	0	4	0	1	1	0	1	0	0	0	0	1	0	0
ARCH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ASPHALT	0	0	1	0	0	2	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
BLOCK	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Cement	3	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
constr	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CONSULT	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Consultant	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
contr	2	2	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	1
dealer	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
educ	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	6	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0
Engr	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
fly ash	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Govt	1	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0	1	0	0	0	0	0	1	2	0	0	1	1	1	0	0	1
Lab	0	0	0	0	0	0	0	1	1	1	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1	0	1	0	0	1	0	0	0	1
M	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Owner	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
pave	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0
PIPE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Premix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reseller	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RM	10	2	0	1	1	8	3	13	3	0	3	0	12	1	0	1	1	2	3	9	4	4	1	0	7	1	12	1	4	4	0	6	1	0	0	1	2	1	4
RMB	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
RMM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
Count	27	5	2	1	2	14	3	29	7	1	3	1	19	3	2	3	1	4	4	14	9	6	10	1	10	2	24	2	7	8	4	9	1	2	2	3	3	2	7

Figure G3. (Sheet 3 of 6)

seeMix sales from 11/1/89 to 4/24/95 (Under CPAR)

MSt																				
NY	OH	OK	ON	OR	PA	PEI	PR	QB	RI	SC	SD	SO	TN	TRANSVAAL	TX	UT	VA	WA	WI	COUNT
0	2	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	6
2	4	0	1	1	2	0	0	0	0	0	1	0	1	0	1	0	3	2	1	56
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	10
1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
1	0	0	3	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	15
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	16
1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	6
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
1	0	1	0	1	2	0	0	0	1	0	0	0	1	0	1	1	2	0	0	25
1	1	0	0	0	0	0	0	1	0	1	0	0	0	1	3	0	0	1	0	20
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	1	1	0	0	2	0	0	0	0	2	0	0	0	0	1	0	1	1	0	15
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
4	8	0	5	2	5	0	2	0	0	1	1	1	5	0	7	4	5	8	4	188
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
14	19	2	10	6	15	2	2	1	1	4	2	1	7	1	16	5	13	12	5	395

Figure G3. (Sheet 4 of 6)

seeMix sales from 11/1/89 to 4/24/95 (Under CPAR)

Type	MSt																																						
		AB	AK	AL	AR	AZ	BC	CA	CO	CT	FL	GA	HI	IA	ID	IL	KS	KY	LA	MA	MB	MD	ME	MI	MN	MO	MP	MS	NC	ND	NE	NF	NH	NJ	NM	NS	NV	NY	OH	OK
Admix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
AGG	7	0	2	5	1	2	0	7	3	0	3	0	1	2	0	1	7	0	1	1	0	6	1	2	4	2	0	0	0	1	1	1	2	0	0	1	0	4	5	3
apave	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
ASPH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Asphalt	0	0	2	0	1	1	0	3	0	1	0	0	2	1	1	0	3	0	0	0	0	1	0	3	3	0	0	0	0	0	0	0	2	1	1	0	0	3	0	0
Cement	7	0	0	0	0	4	0	2	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
constr	0	1	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CONSULT	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Contr	0	1	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0	0	0
crusher	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Educ	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	6	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
engr	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
fly ash	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
govt	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	1
Lab	0	0	1	0	0	0	1	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0	0	0	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0
ltwt	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
pave	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
paving	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PC	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
premix	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RM	6	4	0	4	0	5	1	15	4	2	1	1	3	1	1	1	4	0	1	0	1	8	0	5	2	2	1	0	1	0	1	0	0	1	1	0	4	6	7	0
Count	21	6	7	15	2	14	2	30	10	3	5	3	8	4	6	3	15	2	2	1	3	15	1	17	11	7	1	1	2	2	3	2	8	2	3	1	4	14	14	5

Figure G3. (Sheet 5 of 6)

seeMix sales from 11/1/89 to 4/24/95 (Under CPAR)

MSt																	
ON	OR	PA	PEI	PR	RI	SC	SC	SO	TN	TRANSVAAL	TX	UT	VA	WA	WI	-	COUNT
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
2	0	3	0	0	0	1	2	0	0	0	6	2	4	1	1	0	98
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	2	0	0	0	0	1	0	0	0	0	0	0	1	0	0	33
0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	18
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	9
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	13
0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	11
0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	10
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	8
0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1
0	0	4	0	1	1	2	1	1	3	0	3	4	7	8	2	0	131
2	1	12	2	1	1	3	4	1	3	1	13	6	15	13	3	1	357

Figure G3. (Sheet 6 of 6)

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13. ABSTRACT *(Maximum 200 words)*

This report presents the results of a research program to develop a computer software program, SmartPlant, which could reduce the cost of concrete mixtures and increase construction productivity by minimizing the adverse effects of materials and mixture variations upon construction operations.

SmartPlant is comprised of five component programs. Most attention was given to seeMIX, the mixture proportioning program. A laboratory evaluation of this program was conducted in which simulated paving, structural, and mass concrete mixtures were proportioned using current American Concrete Institute (ACI) proportioning practices and seeMIX technology. Two field evaluations of seeMIX were also conducted. SeeMAT-A, the aggregate database program, was also evaluated under field conditions on two occasions. SeeMAT-C, the cement database program, and seeMAT-P, the pozzolan database program, were evaluated in the laboratory. SeeSTAT, the statistical database program was not evaluated.

The results indicated that seeMIX mixture proportioning technology can proportion concrete mixtures having fresh and hardened properties equal to, and in some instances superior to, current ACI proportioning practices when richer mixtures, such as those used in paving or structural applications, are being proportioned. SeeMIX was less effective in proportioning lean mass concrete mixtures. SeeMAT-A, seeMAT-C, and seeMAT-P performed well and were judged to be useful tools, both as components of SmartPlant and as stand-alone tools.

While the individual components of SmartPlant were evaluated, numerous logistical and technical problems prevented the evaluation of a fully automated SmartPlant system either in the laboratory or the field.

14. SUBJECT TERMS

Aggregate blending	Concrete aggregates	SeeMAT-C
Aggregate particle distribution	Concrete mixture proportioning	SeeMIX
Combined aggregate grading	Concrete workability	SeeMAT-P
Concrete	SeeMAT-A	SmartPlant

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